

TOWARDS DEVELOPING A DOUBLE CROPPING SYSTEM BETWEEN WINTER
BARLEY AND SOYBEAN IN THE UPPER MIDWEST

A THESIS

SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL

OF THE UNIVERSITY OF MINNESOTA

BY

Hang Becky Zhong

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF SCIENCE

Kevin Smith and Aaron Lorenz, Advisors

September 2019

© Hang Becky Zhong 2019

ACKNOWLEDGEMENTS

There are many people I would like to acknowledge who have given me guidance, support, and advice during my graduate study at the University of Minnesota (UMN). I want to first thank my advisors, Dr. Kevin Smith and Dr. Aaron Lorenz for giving me an opportunity to conduct research and study at UMN. I am extremely grateful for all the advice and mentorship that my advisors have provided me over the course of the last three years. Before coming to Minnesota, I must say that I have not experienced a “real winter” for many years, and I am so glad for the many experiences during the past three winters that I had in Minnesota, especially the times when I wondered if it would be me or my research experimental subjects: winter barley that will survive the long winters.

Thank you to my committee members, Dr. Nancy Ehlke, and Dr. Brian Steffenson for giving me guidance and support along my graduate career here at UMN. I also want to thank Dr. Craig Sheaffer for allowing me to be a Teaching Assistant in AGRO 1103, where I learned so much about undergraduate teaching and truly enjoyed working with such a diverse and wonderful cohort of students. Thank you to Dr. Jochum Wiersma, Dr. Scotty Wells, and Dr. Seth Neave for giving me agronomy advice on winter barley, soybean and the overall cropping system between winter barley and soybean. Thank you to Dr. Paul Porter for supporting me to apply and eventually attend the 2018 Chicago Council on Food Security Symposium. What an incredible experience! Thank you to Dr. Mary Brakke for allowing me to conduct a survey research project on undergraduate teaching and writing. I would like to thank Dr. Craig Sheaffer and Dr. Don Wyse, along with Department Head Dr. Nancy Ehlke and Associate Dean Dr. Gregg Cuomo for giving me tremendous amounts of support during the most traumatizing periods of my graduate school experience. Thank you all for giving me thoughtful advice and encouragement that have enabled me to stay focused and even more determined towards my academic dream.

I also want to thank Ed Schiefelbein, Guillermin Velasquez, Sonia Bolvaran, Steve Quiring, Tom Hoverstad, Alex Hard, Eric Ristau and many other technicians for helping me with all the research plot designs and field trials. I will never forget the many memorable experiences I have had with our wonderful field crews in both soybean and barley breeding labs. I would not be able to accomplish anything without your help. I am also very grateful to many undergraduate student workers who have helped me with field work and data curation.

Thank you to my life-long mentor, Professor Rich Kamens for giving me so much wonderful advice and encouraging me to pursuing research in an interdisciplinary field. Thank you to Dr. Shabbir Gheewala for giving me advice and leading me into a new field for the better future of sustainable agriculture and thinking more towards the “Food-Energy-Water” Nexus. Thank you to Connie Carlson and Colin Cureton for giving me advice on the winter barley interview project. What a great state, and what a wonderful experience for me to connect with so many stakeholders of the malting barley supply chain and learn about their perspectives on the development of winter barley and a winter barley-soybean double cropping system.

Lastly, I am incredibly appreciative of my mother, who have supported me along the way of my graduate school study no matter how dark I felt at times. I am so thankful for everything she has done for me, and for all the encouragement and support she has given me. I am also very thankful of my family in China and the US who have given me great support throughout my graduate school study. Thank you to my fellow APS colleagues and friends for all your kind support and friendship! Thank you to all, and there are just so many people that I am so grateful for since I

came to Minnesota. I would not be able to accomplish what I have done without any one of your help and support.

ABSTRACT

Multiple cropping systems offer the potential of producing crops at the same time as providing ecosystem functions in the same space. Double cropping represents an approach of multiple cropping, which is the practice of planting a second crop immediately following the harvest of a first crop. A winter malting barley and soybean double cropping system presents an area that warrants research efforts in the Upper Midwest. A research project that investigates toward double cropping winter barley (*Hordeum vulgare* L.) and soybean (*Glycine max* L.) was carried out in Minnesota.

The key challenge for winter barley to be successful in cold climates, including Minnesota, is winter survival. A study examining the effect of fall planting dates on winter survival and yield was conducted in southern Minnesota. The objectives were to evaluate the effect of planting date, cultivar, fall growth, and winter weather on winter barley survival. No specific fall planting date from early September to Mid-October affected winter survival. Planting dates that resulted in fall accumulated GDD from 600 to 1400 were associated with better winter survival in years with sufficient snow cover. Less than four inches of snow cover and temperatures at or below -4°F for more than three days led to poor winter survival in five of the eleven site-years.

Double cropping in cold climates could be accomplished using short-season soybeans that can be planted later to allow for a previous crop like winter barley. An experiment was conducted to assess variations of phenology, yield, seed quality, and days to maturity of 23 soybean cultivars in maturity groups 00 to 0 planted around late-June to early July

in a short-season system (SS) compared to soybeans planted in May in a full-season (FS) system across northern and southern latitude regions in Minnesota. Results showed that latitude-cropping system variations had great influence on soybean yield, seed quality, and days to maturity. Significant cultivar x latitude-cropping system effects were found between northern latitude full-season and southern latitude short-season production systems for yield, protein concentration, oil concentration, and days to maturity, and indirect selection may be applicable for these traits between the established breeding program for northern latitude full season and the potential southern latitude short-season production systems. No specific growth stage was associated with yield in the short-season cropping system.

As researchers work to improve the agronomic management and genetic development of a double cropping system between winter barley and soybean in Minnesota, there is a lack of understanding of the economic and environmental perceptions of a potential winter malting barley crop among local farmers and the malting barley end-users. An interview study was conducted to gain information on the views of winter barley in Minnesota among various stakeholders. By sharing the current status of winter barley breeding and agronomic management research, we examined interests and concerns for winter barley and a potential winter barley-soybean cropping system among important stakeholders that included farmers, maltsters, and brewers. Results of this study may aid in determining interested areas and opportunities that researchers and stakeholders could possibly connect and work collaboratively toward the eventual adoption of winter barley and a winter barley-soybean double cropping system on Minnesota cropping landscapes.

TABLE OF CONTENTS

ACKNOWLEDGMENTS	i
ABSTRACT	ii
LIST OF TABLES	vi
LIST OF FIGURES	viii
 CHAPTER 1. THE PRESENT STATUS AND CHALLENGES TOWARDS DEVELOPING A DOUBLE CROPPING SYSTEM BETWEEN WINTER BARLEY AND SOYBEAN IN THE UPPER MIDWEST A REVIEW.	1
1.1 Multiple cropping systems: Ecosystem and economic benefits, and its design implications based on Genotype (G) x Environment (E) x Management (M) interactions	1
1.2 Towards a winter barley-soybean double cropping system in the Upper Midwest	4
1.2.1 Cultivation and use of soybean, and double cropping soybean in the US	4
1.2.2 Cultivation and uses of barley with a focus on the potential of winter malting barley production in the US	8
1.2.3 Feasibilities and benefits of a winter barley-soybean double cropping system: Focusing in Minnesota.....	11
1.2.4 Potential challenges for soybean to fit in a double cropping system	14
1.2.5 Potential challenges for winter barley to fit in a double cropping system	16
1.2.6 Cultivar development and management practices for short-season soybean production	18
1.2.7 Breeding improvement and best management practices for winter barley.....	21
1.3 Assessment of a winter barley-soybean double cropping system.....	25
1.3.1 Stakeholder engagement towards new crop and cropping system development	25
1.3.2 Interview research methodology for understanding stakeholder perceptions	26
 CHAPTER 2: ASSESSMENT OF WINTER BARLEY IN MINNESOTA: RELATIONSHIPS AMONG CULTIVAR, FALL SEEDING DATE, WINTER SURVIVAL, AND GRAIN YIELD	31
2.1 Synopsis	31
2.2 Introduction.....	32

2.3 Field Experiments and Treatment Description	33
2.4 Data Collection and Analysis.....	34
2.5 Results and Discussions.....	36
2.5.1 Environmental Conditions	36
2.5.2 Planting Date and Cultivar Effects on Winter Survival.....	36
2.5.3 Effect of Fall Growth on Winter Survival	37
2.5.4 Effect of Winter Weather Conditions on Winter Survival.....	38
2.5.5 Effect of Winter Survival on Grain Yield.....	39
2.5.6 Future Outlook of Winter Barley Production in Minnesota	39
 CHAPTER 3: DIVERSIFYING SOYBEAN-BASED CROPPING SYSTEMS: EXPLORING CULTIVAR X ENVIRONMENT INTERACTIONS FOR DOUBLE CROPPING SOYBEANS IN THE UPPER MIDWEST.....	
3.1 Introduction.....	50
3.2 Material and Methods	54
3.2.1 Site, Experiment, and Cultivars	55
3.2.2 Measurements	56
3.2.3 Calculations and Data Analysis	57
3.3 Results and discussion	58
3.3.1 Environment.....	58
3.3.2 Cropping System Effects on Seed Yield, Quality, and Days to Maturity Variations	58
3.3.3 Cropping System Variations in Southern Latitude Regions	60
3.3.4 Variations between Soybeans Planted within FS in Northern Latitude and SS in Southern Latitude	63
3.3.5 Breeding Program Implications for Developing SS Soybean in Southern Latitude Regions.....	64
3.3.6 Variation of Growth-Stage Duration in Southern Latitude Regions	67
3.4 Conclusions.....	68
 CHAPTER 4: STAKEHOLDER PRECEPTIONS TOWARDS DEVELOPING WINTER BARLEY AND THE WINTER BARLEY-SOYBEAN DOUBLE CROPPING SYSTEM IN MINNESOTA.....	
4.1 Introduction.....	83
4.2 Research Purpose	87
4.3 Research Methodology	87
4.4 Results.....	89
4.4.1 Farmers	89
4.4.2 Maltsters.....	92
4.4.3 Brewers	93
4.4.4 Stakeholder Engagement Assessment.....	95
4.5 Conclusions.....	95
APPENDIX. Interview guide.....	101
 BIBLIOGRAPHY	106

LIST OF TABLES

Table 1-1. Outline of soybean double cropping studies in the Upper Midwest (2010-2018).	28
Table 2-1. Winter barley cultivars evaluated for winter survival for ten site-years at St. Paul (STP) and Lamberton (LAM), Minnesota.	40
Table 2-2. Targeted and actual planting dates used in evaluating the winter survival for ten site-years at St. Paul (STP) and Lamberton (LAM), Minnesota.	41
Table 2-3. Effect of planting date and cultivar treatments on winter barley survival in four growing seasons at St. Paul and two at Lamberton, MN.	41
Table 2-4. Accumulated growing degree days (GDD) °F (base=32) from actual planting date to freeze-up date for four target planting date treatments used in the evaluation of the winter survival of winter barley cultivars for ten-site years at St. Paul and Lamberton, Minnesota.	42
Table 2-5. Number of days with a lack of sufficient snow coverage in St. Paul from 2010-2013, and 2015-2018, and Lamberton from 2015-2018.	43
Table 2-6. Percent winter survival for three winter barley cultivars at each target planting date for three growing seasons at St. Paul and one at Lamberton, MN.	44
Table 2-7. Effect of planting dates (day of the year) on grain yield of winter barley cultivar McGregor for five site-years.	45
Table 3-1. List of cultivars, source (NDSU: North Dakota State University, UMN: University of Minnesota), pedigree, and relative maturity group.	70

Table 3-2. Experimental details with respect to test sites, soils, and dates of planting and harvest at Lamberton, Waseca, Westbrook, Crookston, and Shelly, MN within full-season (FS) and double cropping (SS) production systems.	71
Table 3-3. Mean monthly air temperature and total monthly precipitation at Waseca, Lamberton, MN (southern latitude region) in 2017 and 2018 growing season and Crookston, MN (northern latitude region) during the 2018 growing season, and during the past 30 years..	72
Table 3-4. Means and ranges of yield, protein, oil, and maturity date for cultivars in northern latitude regions: Crookston and Shelly, MN, and southern latitude regions: Waseca, Lamberton and Westbrook, MN within FS and SS cropping systems.	73
Table 3-5. Mean squares from analysis of variance of yield, protein, oil, and days to maturity for soybean cultivars in Minnesota during 2017 and 2018.	74
Table 3-6. Cultivar and environment effects on yield, protein, oil, and days to maturity for full-season (FS) and double cropping (SS) systems at Waseca and Lamberton, MN in 2017 and 2018, and Westbrook, MN in 2018.	75
Table 3-7. Averages, yield rankings (in parentheses), mean across all the cultivars, and Spearman's correlation coefficients for full-season (FS) and double cropping (SS) systems effect for yield, protein, oil, and days to maturity in southern latitude regions. .	76
Table 3-8. Mean squares from analysis of variance of yield, protein, oil, and days to maturity for soybean cultivars planted in northern latitude-full-season and southern latitude-short-season latitude regions during 2017 and 2018.	77
Table 3-9. Mean squares from analysis of variance of yield, protein, oil and days to maturity in response to cropping system-latitude (North-Full season and South-Short season) effects.	78
Table 3-10. Averages, yield rankings (in parentheses), mean across all the cultivars, and Spearman's rank correlation coefficients for northern-latitude (N) full-season and southern-latitude (S) short-season cropping systems effect for yield, protein, oil, and days to maturity.	79
Table 3-11. Means of days spent in growth stages include vegetative (V), flowering (R1-R3), pod setting (R3-R5), seed filling (R5-R7), complete reproductive phase (R1-R8), and days to maturity (DTM) of all cultivars at FS and SS planting dates (PD) during 2017 and 2018 at Waseca and Lamberton, MN.	80
Table 3-12. Correlations between yield, vegetative (V), flowering (R1-R3), pod setting (R3-R5), seed filling (R5-R7), complete reproductive phase (R1-R8), and days to	

maturity (DTM) at FS and SS planting dates (PD) during 2017 and 2018 at Waseca and Lamberton, MN.	81
Table 4-1. Description of farmers interviewed.	97
Table 4-2. Description of brewers interviewed.	98
Table 4-3. Description of maltsters interviewed.	99

LIST OF FIGURES

Figure 1-1. Map of the Midwest emphasizing the Upper Midwest.	28
Figure 1-2. Illustration of the monocropping soybean production system (left), and a potential winter barley-soybean double cropping system in Minnesota (right). Stars highlight the planting and harvesting time for each crop.	29
Figure 2-1. Maximum temperature per day (blue line), minimum temperature per day (red line), snow depth per day (light blue area), and precipitation per day (dark blue area), presence of four inches of snow depth when minimum temperature is at or below -4°F (black line), and regression analysis of planting date to winter survival 2010-2013 and 2015-2018 at St. Paul, MN.	62
Figure 2-2. Weather conditions include maximum temperature per day (blue line), minimum temperature per day (red line), snow depth per day (light blue area), and precipitation per day (dark blue area), presence of four inches of snow depth when minimum temperature is at or below -4°F (black line), and regression analysis of planting date to winter survival during 2015-2018 at Lamberton, MN.	63

Figure 2-3. Relationship between winter survival and grain yield for the cultivar McGregor at five site-years with greater than 20% average winter survival. Each point represents a plot at each site-year.64

Figure 3-1. Map of all sites and latitude regions in Minnesota. Yellow area indicates the northern-latitude region, and green area indicates the low-latitude regions.82

Figure 4-1. Interviewees were asked to select one of the nexus diagrams of possible relationships between three key stakeholder groups: farmer, brewer, and maltster that they envision for the future of winter and local malting barley supply chain development.100

CHAPTER 1. THE PRESENT STATUS AND CHALLENGES TOWARDS DEVELOPING A DOUBLE CROPPING SYSTEM BETWEEN WINTER BARLEY AND SOYBEAN IN THE UPPER MIDWEST

1.1 Multiple Cropping Systems: Ecosystem and Economic Benefits, and Design

Implications Based on Genotype (G) x Environment (E) x Management (M) Interactions.

The challenge of agriculture today is to contribute to current and future food security, limit the adverse effects on the environment, and produce ecosystem services (Gesch et al., 2014; Tilman et al., 2002). Intensive farming practices associated with monospecies cropping systems, also known as ‘monocropping’ deliver provisional services such as food, fiber, and feed, but fall short in environmental protection and ecosystem services (Gaba et al., 2015; Tilman et al., 2002). Complete reliance on conventional monocropping simply cannot meet this challenge. Multiple cropping systems can produce crops while providing several ecosystem functions in the same space (Gaba et al., 2015). At the field scale, multiple cropping systems may include annual crops grown together (Litrice and Violle, 2015), or grown in subsequences (Gaba et al., 2015). Numerous studies have shown that multiple cropping systems reduce soil erosion and nutrient loss (Dabney, 1998), and act directly on soil fertility by improving soil organic matter and promoting N₂ fixation through legumes (Di and Cameron, 2002; Dinnes et al., 2002; Tiemann et al., 2015). Multiple cropping systems use lower amounts of synthetic agrichemical inputs compared to monocropping systems (Davis et al., 2012). A long-term multiple cropping system study that included red clover (*Trifolium pretense*) or alfalfa (*Medicago sativa*) grown overwinter prior to planting corn (*Zea mays*) in Ontario showed that such crop diversification systems increased the chance of capturing favorable growing conditions and yield for the corn

crop (Gaudin et al., 2015) than monocropping corn. In addition, improved pollinator health has been reported in multiple cropping systems through increased nectar production when oilseed crops such as pennycress, winter camelina, and winter canola were planted as winter cover crops in South Dakota (Eberle et al., 2015).

There are several types of multiple cropping systems. Double cropping, also known as sequential cropping, is the practice of planting a second crop immediately following the harvest of a first crop, thus harvesting two crops from the same field in one year. However, double cropping requires a sufficiently long growing season and crops that mature quickly enough to allow two harvests in one year. Relay-intercropping is a technique in which different crops are planted at different times in the same field, and both (or all) crops spend at least part of their season growing together in the field. Strip cropping involves two or more crops planted in strips such that most plant competition occurs within each crop rather than between crops in the same field (Nafziger, 2012).

In particular, double cropping has been reported to use climatic, land, labor, and equipment resources more efficiently and produce more total grains per year (Crabtree et al., 1990; Sandler, 2014). Overall farm management can be greatly improved with double cropping because equipment and personnel work load distribution are more evenly spread out (Holshouser, 2016). Moreover, previous research has indicated that a double cropping system between soybean and winter wheat improved the capture and efficient use of annual precipitation and photosynthetically active radiation (PAR) in comparison to monocropping wheat (*Triticum aestivum* L.) and soybean (Caviglia et al., 2004).

Yields of major commodity crops have increased over time due to three major factors: improved genetics (G), improved management (M), and environmental (E) adaptations (Hatfield

et al., 2015). These factors may apply towards the development of crops that fit into a multiple cropping system, especially double cropping. Plant breeding improvement has traditionally focused on optimizing the agronomic value, particularly the harvestable yield of a single crop (Litrico and Violle, 2015). Brakke et al. (1983) found significant effects of cropping system, environments within each cropping system, genotype, and genotype by cropping system for days to flower, yield, and harvest moisture in corn between an “ecofallow” (double cropping with winter wheat) and conventional cropping systems. The authors concluded that maximum corn yields can be achieved in Nebraska by developing specific cultivars for each cropping system in distinct environments (Brakke et al., 1983). Holland and Brummer (1999) compared the cultivar rankings of oat (*Avena sativa* L.) in monocropping and intercropping systems with berseem clover (*Trifolium alexandrinum* L.) in Iowa. The authors concluded that the productivity of the oat–berseem clover intercrop will more likely be improved through the agronomic productivity improvement of berseem clover in the intercropping cropping system (Holland and Brummer, 1999). Another study comparing corn monoculture, corn-bean intercrop, and corn-clover intercrop showed more similarities for corn yield between the intercrops than between either intercrop and monoculture, leading the authors to conclude that selection of hybrids adapted to corn-clover intercrop or corn-bean intercrop are more preferred (O’Leary and Smith, 1999).

However, it was not until more recently that scientists began to suggest plant breeding efforts toward the development of multiple cropping systems for enhanced environmental and ecosystem services (Robertson and Swinton, 2005; Runck et al., 2014). In addition, there has been a rapid growth of the local agriculture movement across the US in recent years. The “locavore” movement has encouraged deeper connections among end-users, growers, plant breeders and agronomists (Brouwer et al., 2016). Selection of plant varieties specifically adapted

to multiple cropping systems and local end-use markets may become an important component of building a resilient food system (Brouwer et al., 2016). Informed plant breeding decisions for a double cropping system may create significant impacts if the positive ecosystem and economic valuations are disseminated and adopted by local communities and the society at large.

1.2 Towards a winter barley-soybean double cropping system in the Upper Midwest.

1.2.1 Cultivation and use of soybean, and double cropping soybean in the US. Soybean is one of the most important legume crops utilized and consumed worldwide. Originally from China, soybean is one of the oldest domesticated crops on earth (Sheaffer and Moncada, 2012). Historical evidence reports the first utilization of soybean as a food crop in Northeastern China around 1700–1100 B.C. (Hartman et al., 2011). Today, soybean is grown across a wide range of latitudes throughout the world. In the US, soybean is grown in approximately 30 states (Mourtzinis and Conley, 2017), spanning latitudes from 30°N to 50°N, and encompassing regions from southern Texas to the northern tip of North Dakota. In Brazil, soybean production has expanded to very low latitude regions between 15°S and 5°N (Chang et al., 2015; Goldsmith, 2008) due to breeding efforts of extending the long juvenile period in soybean production (Chang et al., 2015). In China, soybean is grown from 19°N to 50°N, and elevation ranges from 50 to 3000 meters (Wang et al., 2001). Top five countries for soybean production each year include the US (~124 million metric tons), Brazil (~123 million metric tons), Argentina (~53 million metric tons), China (~17 million metric tons), and India (~11 million metric tons) (Chang et al., 2015; USDA Foreign Agricultural Service, 2019). In the US, the top three states with the most soybean production are all concentrated in the Upper Midwest, and they include Illinois (~11 million acres), Iowa (~10 million acres), and Minnesota (~8 million acres) (National

Agricultural Statistics Service (NASS), 2018). Virtually all the soybean produced in this region is monocropped in dryland production systems in rotation with corn (Borchers et al., 2014).

Soybean is an annual plant in the Fabaceae family. It is a self-pollinating and diploid plant with 20 chromosomes ($2n=40$) (Liu et al., 2016). The 1.1 gigabase soybean genome includes 46,430 genes (Greilhuber and Obermayer, 1997; Zhang et al., 2015). Most genes (~75%) have multiple copies due to soybean genome duplications, which occurred at approximately 59 and 13 million years ago (Schmutz et al., 2010). Soybeans, compared to most crops, have limited genetic diversity which offers challenges to crop improvement (Bandillo et al., 2017). There are two types of soybeans grown in the US. Indeterminate, which is mostly grown in the Upper Midwest, and determinate, which is mostly present in the southern regions of the US (Sheaffer and Moncada, 2012). Reproductive and vegetative development co-exist after the appearance of the first flower in indeterminate types, whereas in determinate and semi-determinate soybean genotypes, vegetative activity ends at the stem apex, and reproductive growth begins when apical meristem eventually becomes a raceme (Egli, 2011; Setiyono et al., 2007). As a legume, soybean is capable of fixing its required N using biological nitrogen fixation (Herridge et al., 2008; Stoyanova, 1996). The subsequent crop in a crop rotation program can utilize residual nitrogen remaining in the soil and thus reduce the need of synthetic N input (Bundy et al., 1993; Park et al., 2005; Keyser and Li, 1992).

Along with its dissemination worldwide, soybean has adapted to various cropping systems and growing environments, especially to the local day length and temperature conditions (Liu et al., 2017). In the Upper Midwest, full-season soybean planting typically peaks during mid to late May (Kandel and Endres, 2019; Specht et al., 2012). Originally a short-day plant, soybean is known to be highly sensitive to temperature and photoperiod (Board and Hall, 1984; Egli and

Bruening, 1992; Emerson Nafziger, 2012; Liu et al., 2017). Temperature can influence the rate of crop growth, but more importantly, photoperiod impacts the temperature response in soybean, in that long daylength slows the developmental rate (Miladinovic et al., 2006; Setiyono et al., 2007). Over the years, soybean production has expanded to extremely high latitude regions through the introduction of early maturing and photoperiod-insensitive varieties (Cober and Voldeng, 2012; Wilcox, 2001; Xu et al., 2013).

Major diseases for soybean in the Upper Midwest include *Phytophthora* root rot (*Phytophthora sojae*), soybean cyst nematode (*Heterodera glycines*), and *Rhizoctonia* damping-off and root rot (*Rhizoctonia solani*). A major pest to soybean production is soybean aphid (*Aphis glycines*) (Chen et al., 2007; Kandel and Endres, 2019; Knodel et al., 2018; Wrather et al., 1997). Various research studies have concluded that different planting dates for soybean can greatly influence its exposure to insect pests (Hammond et al., 1991; Zeiss and Klubertanz, 1994), and soybean diseases (Grau et al., 1994; Shrestha and Lindsey, 2019).

Due to its high protein and oil content, and functional composition such as isoflavones, soybean is rich in nutritional value (Hartman et al., 2011; Liu et al., 2017; Singh and Hymowitz, 1999). It is estimated that protein ranges from 30-48% with an average of 40%, and oil ranges from 13-22% with an average of 20% in a soybean seed (Singh and Hymowitz, 1999; Wilson, 2004). Soybean oil can be converted to margarine, mayonnaise, shortening, salad oils, and salad dressings. Soybean protein meal is used primarily as a source of high-protein feeds for the production of livestock (Johnson et al., 2008). Soybean is also directly consumed by people worldwide, popular soybean food items include edamame, tofu, soy milk, and soy sauce (Johnson et al., 2008).

Plant breeders have been releasing soybean varieties based on maturity group (MG) zones that represent defined areas where a cultivar is best adapted in the US (Mourtzinis and Conley, 2017). The MG designation for soybean cultivars in the U.S. is based on soybean development response to photoperiod (Boerma et al., 2004; Setiyono et al., 2007). MG ranges from 00 in North Dakota for the very early maturing varieties to X in Florida (Boerma and Specht, 2004; Zhang et al., 2007). In the Upper Midwest, MG of 00 to III are commonly planted for mono-cropping purposes (Mourtzinis and Conley, 2017).

Double cropping soybeans, also called short-season soybeans are planted in June to July, and harvested in October to November so a winter annual can be planted again within a double cropping system in the Upper Midwest (Berti et al., 2017; Johnson et al., 2017). A major challenge for planting dates that extend into June and July is that soybean yield often decreases substantially (Emerson Nafziger, 2012; Wesley, 1999). Historically, double cropping soybean production is commonly practiced in the Upper and Mid-south regions of the US due to much later fall frost dates and longer growing seasons observed in these regions (Browning et al., 2011; Camper et al., 1972; Egli and Bruening, 2000; Holshouser, 2014; Thomason et al., 2017). Winter wheat is the most common winter annual crop paired with soybean in a double cropping systems in these regions (Kyei-Boahen and Zhang, 2006). In addition, the acreage devoted to double cropping in the Southeast US depends heavily on the commodity prices of both the winter annual and soybean. When soybean prices are relatively high, more farmers would choose to plant full-season soybean than double cropping to maximize yield and profit (Borchers et al., 2014).

Available research about double cropping soybean in Southern US might not be relevant or readily applicable to the growing conditions in the Upper Midwest. While there is interest to

incorporate soybean in double cropping systems with winter annuals (Gesch and Archer, 2013; Moore and Karlen, 2013), currently no cultivar development or breeding program has been established for double cropping soybean production in the Upper Midwest.

1.2.2 Cultivation and Uses of Barley with a Focus on the Potential of Winter Malting

Barley Production in the US. Barley (*Hordeum vulgare* L.) is one of the most ancient crops still grown and used around the world. Domesticated around 10,000 years ago in the Fertile Crescent (Badr et al., 2000), barley is extremely adaptable to a wide range of growing environments, though much of the world's barley is produced in regions where cereals such as maize and rice cannot grow well (Zhou, 2009). The production range for barley includes a subarctic growing region that extends as far as 70° north latitude, and a subtropical zone of cultivation that extends into North Africa. Furthermore, barley is cultivated at elevations as high as 4,000 m (13,120 ft) in the Andes and as high as 4,700 m (over 15,415 ft) in the highlands of Tibet (Hertrich, 2013). It ranks fourth in both quantity produced and in area of cultivation of cereal crops in the world (Zhou, 2009). The top five countries or regions with the most barley production (by metric tons) in the world include European Union (~58 million metric tons), Russia (~20 million metric tons), Australia (~8 million metric tons), Canada (~8 million metric tons), and Ukraine (~7 million metric tons), (USDA Foreign Agricultural Service, 2019). The United States produced 3.12 million metric tons of barley in 2017-2018, and the majority of barley is produced in the northern and western states, with most production in Montana, North Dakota and Idaho (National Agricultural Statistics Service (NASS), 2018).

Utilization of barley is highly diverse. Historically, barley was introduced to the United States by European immigrants and has now become an important crop for both animal feed and malting end-use (Hertrich, 2013; Roth et al., 2016). Globally, animal feed is the largest use of

barley, accounting for about 60% of global consumption (Ullrich 2010). However, in the United States, approximately 66% of the barley grain produced is used in food and beverage (primarily as malt) and industrial products, while 22% is used in feed and byproducts, and 12% is exported (U.S. Grains Council, www.grains.org).

A plant in the Poaceae family, barley is a cool-season annual plant that is naturally self-pollinating (Ullrich, 2010), and it is a diploid species with seven chromosomes ($2n=2x=14$), designated as 1H to 7H according to their homeology to other species in the Triticeae (Graner et al., 2010). The barley genome is estimated at a haploid size of about 5.1 gigabases (International Barley Genome Sequencing et al. 2012). There are two types of barley: two-rowed and six-rowed types commonly grown in the world (Garstang et al., 2011). The difference between six-row and two-row types is genetically controlled by the Vrs1 gene (Komatsuda et al., 2007). Both six-row and two-row barley can be planted either in the spring or fall to be used for malting (Gallagher, 1983). In recent years, two-row barley has dominated the malting barley production in the US as two-row kernels are more uniform in size and can be crushed more effectively than the laterals of six-row types, and thus produce more barrels of beer. The brewing industry supported research that led to higher enzyme levels and other improvements to two-row varieties (Hertrich, 2013; Springer, 2018).

Planted in the fall, winter barley will overwinter, and eventually mature by the subsequent summer. Winter barley generally reaches grain maturity approximately three to four weeks earlier than spring barley (Culman et al., 2017). The growth habit of winter barley can be classified as the true winter type that requires vernalization or facultative that does not require vernalization (Kirby et al., 1985). Facultative winter barley types can be planted in the spring or fall and may offer flexibility of planting choices to growers (Hayes et al., 2012; von Zitzewitz et

al., 2005). Previous research has shown that winter barley has an advantage in weed suppression, and could be grown with no herbicide applications (Dhima et al., 2006). When compared with winter wheat, winter barley requires less nitrogen application to achieve acceptable yields, which enables this crop to perform better in low-input conditions (Delogu et al., 1998). As a result, the reduced N requirements makes winter barley a better choice to reduce surface and groundwater pollution due to nitrate leaching in winter and early spring.

The top five countries for winter barley production are: Germany, France, United Kingdom, Czech Republic, and Denmark. Winter barley growing in the US had less than 1% of the total barley production (Hertrich, 2013), and is mostly grown in the Mid-Atlantic states from Pennsylvania south into Virginia (Lazor, 2013), with most of its production aimed for animal feed. Winter barley has been reported to exhibit lower protein content than spring barley (Batal and Dale, 2016), which makes it an ideal crop to be used for malting purposes. Malting barley generally receives a higher premium price than that for feed barley (National Agricultural Statistics Service, 2018).

In general, malting barley grain should have high germination ($\geq 95\%$), low protein ($\leq 125 \text{ g kg}^{-1}$ on a dry-weight basis), high plumpness ($>900 \text{ g kg}^{-1}$ and $>800 \text{ g kg}^{-1}$ retention on a 2.38-mm slotted screen for two-row barley and six-row barley, respectively), low deoxynivalenol (DON) levels ($<1 \text{ mg kg}^{-1}$), high test weight, minimal skinned and broken kernels ($<5\%$), intact kernels and husks, kernel uniformity, free from blight and other diseases, and no signs of pre-harvest sprouting (American Malting Barley Association, 2014; Kendall, 1994). Previous research has also shown that winter barley can out yield spring barley by 5 to 50% (del Moral and del Moral, 1995; Raun and Johnson, 1999). Furthermore, winter barley is more water-use efficient since it utilizes moisture from spring snow thaw (Szűcs et al., 2007; von Zitzewitz et al.,

2005). Planting winter barley in the fall may also avoid the year to year variability of spring field work (Hertrich, 2013).

1.2.3 Feasibilities and Benefits of a Winter Barley-Soybean Double Cropping System:

Focusing in Minnesota. The Upper Midwest represents the largest row crop production region in the US (National Agricultural Statistics Service (NASS), 2018). It generally consists of three states, which includes Minnesota, South Dakota, North Dakota, and may include parts or the entire state of Iowa, Wisconsin, and Nebraska (Maxwell et al., 2008; Morton et al., 2015). A corn-soybean rotation system currently dominates the cropping landscape in the Upper Midwest. In 2017, over 17 and 14 million acres of corn and soybean were planted in this region. Full-season soybeans were reported to be planted 95% of the times (Johnson et al., 2017; National Agricultural Statistics Service (NASS), 2018), and are typically planted in late-April to early May and harvested from September to early November (Wright et al., 1999).

In recent years, there is a growing interest to diversify the current cropping landscape by planting soybean with winter cash cover crops to take advantage of the fallow period (Johnson et al., 2017; Lund, 2015; Ott et al., 2019). The extensive summer annual cropping systems in Minnesota are actively growing for only a few months, leaving fields fallow for much of the year. Without crops covering the land, fallow ground is vulnerable to erosion and nutrient runoff (Dinnes et al., 2002; Noland et al., 2018; Staver and Brinsfield, 1998). Nutrient and fertilizer runoff can buildup in lakes, streams and rivers and negatively affect water quality (Goolsby et al., 2001; Kladivko et al., 2004). Cropland accounts for 51% of the total land area in Minnesota (National Agricultural Statistics Service (NASS), 2018), and agricultural land management choices can have major effects on water quality (The Water Resources Center, 2017). After

harvesting soybeans, planting a winter cereal crop may reduce residual soil N and therefore N leaching by converting it to crop biomass N (Fraser et al., 2013; Zhu and Fox, 2003).

One winter cash crop that could be planted following the immediate harvest of soybean is winter barley. Craft beer is now established as a vibrant segment of the US beverage industry (Graefe et al., 2018), and the number of craft breweries nearly doubled from 2013 (3814) to 2018 (7346) across the nation (Brewers Association, 2018). Many craft malt houses have been created in response to the rapidly growing North American craft brewing industry in recent years (Brouwer et al., 2016; Elzinga et al., 2018; McLaughlin et al., 2014). In Washington (state) for example, more than 30 craft malt houses have opened from 2001 to 2016 with the goal of producing unique malts from regionally grown grains (Brouwer et al., 2016; Thomas, 2013). Similarly in New York, a Farm Brewery License Program was established in 2016 with the goal to incentivize farm breweries to source 20% of their ingredients locally when making malted beverages, and this percentage will increase to 90% by 2024 (Hmielowski, 2017; Stempel, 2016). Winter barley produced in the Upper Midwest that meets the malting standards can potentially fulfill the local market demand (Culman et al., 2017; Hayes et al., 2012).

Furthermore, planting winter barley and soybean in the same year presents a double cropping opportunity in Minnesota (Figure 1-2). This would enable barley to share some of the large acreages traditionally planted to soybean. A winter barley-soybean double cropping system has been established in the Mid-Atlantic region of the US (Camper et al., 1972) for many years, with winter barley produced for feed end-use. In Minnesota, barley has been an important spring-sown crop for more than 130 years, reaching a peak acreage of over 1.2 million acres in 1988 (Ash and Hoffman, 1989). However, spring barley acreage has since been declining, and can be attributed to many complex reasons. One of the reasons is the severe fungal disease pressure

caused by Fusarium Head Blight (caused primarily by *Fusarium graminearum*). One potential advantage of implementing the winter barley-soybean double cropping system in the Upper Midwest could be the reduced severity of Fusarium Head Blight (FHB) disease. Fall planted winter barley typically heads early (early June) and may avoid weather conditions that are the most conducive to FHB infection and development. In addition, soybean is not known to be a host for FHB. Double cropping winter barley and soybean may reinvigorate the barley production in areas that had not seen small grain productions for decades and years in the Upper Midwest. It was reported that winter malting barley grown in the Ohio Valley is harvested approximately 10 days earlier than winter wheat, providing an opportunity for producers to plant double cropping soybean after barley harvest (Culman et al., 2017). Moreover, similar to winter wheat and other winter cereal crops, winter barley planted in a double cropping system may utilize the nitrogen credit provided by the previous soybean crop and lower the N requirement, ultimately maximize economic returns and reduce the potential risk of nitrate losses through leaching or denitrification (Gaudin et al., 2014; Varvel and Peterson, 1990; Yamoah et al., 1998).

Developing a winter malting barley and soybean double cropping system in the Upper Midwest where double cropping soybean has not been traditionally produced will require additional research. New winter barley varieties, soybean MG and variety evaluations, improved agronomic practices, and rigorous economic analyses are needed before this cropping system can be fully established on the Minnesota cropping landscape. Research on winter barley and double cropping soybean crops individually, and the eventual integration of these crops in a double cropping system will be necessary to determine breeding targets, agronomic management strategies, and enterprise budgets to make this cropping system economically and environmentally viable and adopted by growers and other supply chain stakeholders.

1.2.4 Potential Challenges for Soybean to Fit in a Double Cropping System. Yield for double cropping soybean is often reduced compared to a full-season soybean production system. Previous planting date studies show that average yields are generally similar for soybeans planted until mid-May, but begin to decline rapidly as delayed planting occurs in June for most of the soybean producing areas in the US (Egli and Bruening, 1992). In southern Minnesota, yield loss was around 20% for soybean planted in early June, and the yield loss increased to 43% when soybeans were planted in late June (Wright et al., 1999). In Nebraska, Bastidas et al. (2008) found that yield ranged from a low of 3.6 Mg ha⁻¹ to a high of 4.1 Mg ha⁻¹ for MG III cultivars, and a 12% reduction in relative yield performance was observed in delayed planting in mid-June when compared to a full-season planting date in early May. Salmeron et al., (2014) found that the genotype by environment (G×E) interaction accounted for 22 to 38% of the total yield variability in a study of 16 cultivars (MG III-VI) at four planting dates ranging from early April to late June in 10 locations throughout latitudes ranging from 30.6 °N to 38.9 °N. Egli (2008) analyzed soybean yield trends from 1972 to 2003 in four states: Iowa, Nebraska, Kentucky, and Arkansas, and found double cropping soybeans associated with stagnant yields in Kentucky. Egli and Cornelius (2009) found that grain yield began to decline rapidly when planting date was later than May 27th in the Southeast US, regardless of MG. Delayed planting, particularly for double cropping soybean production purposes have severely reduced soybean yield across various cropping landscapes.

In addition to yield, delayed-planting in a double cropping system greatly affects soybean development throughout the growing season. Reduced soybean yield can be affected by the reduced duration of reproductive phases, water and nutrient availability, and the amount of stubble of the previous winter crop (Caviglia et al., 2011; Hansel et al., 2019). Many research

studies conducted in the Southeast US have indicated that soybeans planted within double cropping conditions can result in shorter plants with fewer nodes (Egli and Bruening, 2000; Salmeron et al., 2014), smaller vegetative mass at the beginning of seed filling (Egli and Bruening, 2000; Kane et al., 1997; Purcell et al., 2002), reduced flowering to pod-set period (Egli and Bruening, 2000), and compromised light interception due to incomplete canopy closure and a shorter growing season (Ball et al., 2000; Purcell et al., 2002; Salmeron et al., 2014). In particular, plant height has been questioned as a potential trait related to yield response (Arslan et al., 2006; Hu and Wiatrak, 2012). However, the effect of plant height to yield for indeterminate varieties were found to be inconsistent within double cropping conditions (Wilcox and Frankenberger, 1987; Pedersen and Lauer, 2004). Another study carried out by Pfeiffer (2000) in Kentucky showed that greater plant height of indeterminate and determinate soybean types did not consistently increase yield in the lower yielding double-crop environments, and the selection of tall soybean lines did not provide improved adaptation to the double cropping soybean production system.

Variation in phenology has been extensively studied for double cropping soybean production systems. Board and Hall (1984) observed that warm temperatures and short day length encountered in July shortened the vegetative phase of cultivars in MGs V-VIII planted late in Louisiana. Also in Louisiana, Heatherly (2005) reported that the late planting date reduced the duration of both vegetative and reproductive growth stages of MG IV through VI soybean. In Kentucky, flowering and pod set (R1-R5) stages determined the critical period for final yield response in late-planted soybean, whereas seed filling period was not as critical for yield determination in late-plantings (Egli and Bruening, 2000). Weavers et al. (1991) found that the duration of seed filling (R5–R7) was reduced in later planting dates in June and July for both

indeterminate (MG VIII) and determinate (MG VII) varieties in Alabama. Chen and Wiatrak (2010) found that later plantings shortened the duration of flowering (R1–R3) and pod setting stages (R3–R5), but not the seed filling stage (R5–R7) by comparing MGs IV to VIII planted in dates ranging from late April to mid-July in South Carolina. Kane et al (1997) reported that between MGs of 00 to IV, vegetative, pod setting, and seed filling were all correlated with yield at planting dates from late April to early June, except during the late June planting date in Kentucky. It is important to note that many studies have identified the reproductive period to affect yield for soybeans planted within a double cropping system, though no specific duration of the reproductive period was confirmed to cause yield variations.

1.2.5 Potential Challenges for Winter Barley to Fit in a Double Cropping System. A lack of sufficient winter hardiness to reliably survive the harsh Minnesota winters presents the most critical challenge for winter barley production. Compared to winter wheat and winter rye, winter barley is more susceptible to damage caused by low temperature (Andrews and Pomeroy, 1981). In environments such as the Upper Midwest, it was once impossible to incorporate fall-sown barley in any crop production system due to its sensitivity to harsh winter conditions (Hayes et al., 2012; USDA-Natural Resources Conservation Service, 2016). Therefore, winter barley has been grown only as a cover crop in such environments, and the cover crop is not harvested for grain (Midwest Cover Crops Council (MCCC), 2012; USDA-Natural Resources Conservation Service, 2016).

Winter barley must cope with cold stress while simultaneously defending itself from diverse pathogens and pests. In addition, barley in general is more susceptible to diseases and pathogens during a hot and humid climate in the early fall (Dickson et al., 1979). The most economically significant disease in Minnesota is FHB, also known as scab (McMullen et al.,

2012). FHB can cause yield losses by reducing kernel development (Paulitz and Steffenson, 2011). The fungus causing FHB produces mycotoxins such as deoxynivalenol (DON), which is harmful to humans and animals (Burrows 2012). For this reason, the threshold for DON content in malting barley is very low (< 1 ppm), and infection is favored by prolonged wet weather and high humidity (Paulitz and Steffenson, 2011). Typical signs of FHB on barley include tan to dark brown lesions at the base of the kernels. Infections of FHB can spread up the entire kernel within a few days under warm, moist conditions. Early infections result in complete sterility of florets, whereas late infections may only reduce yield slightly (Paulitz and Steffenson, 2011).

In addition, several foliar diseases may affect winter barley in the Upper Midwest. Powdery mildew is caused by a fungus, *Blumeria graminis* (= *Erysiphe graminis* f. sp. hordei) that overwinters on stubble and certain wild grasses. Effective management strategies include planting resistant cultivars of barley, crop rotation, elimination of crop residue, and control of volunteer grains and weed hosts reduce inoculum survival from one season to the next for powdery mildew (Paulitz and Steffenson, 2011; Stuthman et al., 2007). Leaf rust is a highly important rust disease caused by *Puccinia hordei* Oth, and its symptoms include orange-brown pustules full of dusty spores that can be observed on the leaf surface and are often surrounded by a chlorotic halo. This disease can be controlled by foliar fungicides, particularly those with systemic action, such as triadimefon. For most situations, the use of resistant cultivars is the best and most useful control measure (Mathre, 1997). Another disease to consider is Barley Yellow Dwarf, which is caused by the Barley Yellow Dwarf Viruses (BYDV), and is transmitted by aphids (McGrath and Bale, 1990). Winter barley sown in the autumn can be infected early by this pathogen, decreasing both the vigor and winter hardiness of the crop. Barley can also be infected with this disease in the spring time. Symptoms caused by BYDV are highly variable due

to host factors (e.g., genotype, age, and physiological condition), and may begin as uneven blotches of bright yellow discoloration on the tips and margins of older leaves. Management of BYDV includes eliminating the grass hosts to reduce the inoculum because BYDV has an extensive host range. It is likely that these diseases will become more prevalent as more winter barley is grown in the region.

1.2.6 Cultivar Development and Management Practices for Short-Season Soybean

Production. Plant growth is a function of both genotype and environment (Shank and Adams, 1960), and the interaction between genotype and environment (G X E). The extent of genotype-by-environment interactions will determine whether a breeding program should be dedicated to develop cultivars specifically adapted to a “target environment” or cropping system (Brakke et al., 1983). In the US, there is currently no evidence of any specific breeding effort on the development of soybean cultivars for a double cropping system with winter barley. Crop performance traits important to a double cropping soybean may include (1) yield; (2) quality characteristics; (3) early season vigor (important for reduced tillage conditions that are preferred in double cropping systems); (4) disease resistance; (5) insect resistance; (6) lodging resistance or standability (Alley and Roygard, 2002). Breeding improvement for these traits could help to develop more appropriate soybean cultivars suitable for double cropping production systems. Carter and Boerma (1979) conducted the first study on late planting soybean genetic variation, and they found significant genotype \times planting date interactions for seed yield, lodging, flowering date, height at flowering, and height at maturity when soybeans of MGs VI and VII were planted at a normal date (late-May) and late date (late-June) in Georgia. They suggested using a separate selection program for double cropping systems. However, Panter and Allen (1987) reported that it is not necessary to establish a double cropping soybean breeding program

in Tennessee. They determined that the determinate F4-derived lines of MG IV-V yielded significantly more in double cropping trials, and the double cropping yield of both indeterminate and determinate types can be predicted from full-season production yield.

Cultivar selection has been evidenced as the single most important decision for maximizing economic returns without incurring additional expenses, especially as it pertains to the choice of maturity group (MG) to be used for double cropping soybean production (Boersma, 2018).

Moving cultivars developed for full-season soybean production systems based on their designated MG has been a common practice for double cropping soybean production. The influence of soybean MG on grain yield will be highly important for growers to be aware of and understand (Shrestha and Lindsey, 2019). Using later MG cultivars is often recommended by extension services in the U.S. Midsouth for double cropping soybean production systems, where late maturities at late plantings can benefit from greater rainfall and mild temperatures at the end of the growing season (Purcell et al., 2003; Salmeron et al., 2014). An explanation for this is the long growing season in the southeast (Chen and Wiatrak, 2010). Egli and Bruening (2000) concluded that the only advantage of using early-maturing cultivars was their earlier maturity without significant yield loss. However, this strategy will not be applicable in the Upper Midwest due to a much shorter growing season (Boersma, 2018). Double cropping soybean production has been traditionally limited in the Upper Midwest due to the increased likelihood of receiving a fall frost prior to soybean maturation. Although in recent years, several research studies have explored moving full-season soybean cultivars of earlier MGs that were developed in higher latitude to a region in lower latitude for double cropping soybean production in the Upper Midwest (Table 1-1).

In addition, various research studies have examined the effect of management practices for double cropping soybean production systems. In Ontario, Canada, soybeans planted at a higher density closed the canopy faster and established the maximum pods per acre possible since plant branching, canopy development, and the number of nodes per plant are limited with late seeding when double cropping soybean was followed by the harvest of winter barley (Richter et al., 2013). Egli and Bruening (2000) found that in Kentucky, the narrow row-high population treatment did not consistently produce higher yields in either normal or double cropping planting dates for soybean, and the authors suggested that the reduction in seed number per square meter was the primary cause of low yield in late plantings (Egli and Bruening, 2000). To this point, no research has examined management effects on yield response in late planting conditions in high latitude regions include the Upper Midwest.

Unmanned aerial vehicles (UAVs) are useful tools for phenotyping crop growth in field conditions, and may be used to assist breeders in mitigating the yield gap for double cropping soybean as it can bridge the gap between genomics and phenotypes (Yu et al., 2016; Makanza et al., 2018; Castelao Tetila et al., 2017). In particular, UAVs are operated at a low altitude to capture images with sufficient resolution for measuring individual field plots, and they can be deployed on demand to ensure optimal temporal resolution during the crop growing season (Yu et al., 2016). Moreover, lowered costs and easier operational skills are making the UAV-based phenotyping a promising solution for plant breeding programs. Several field stress variations have been detected using the UAV-based phenotyping systems for soybeans, and they include maturity classification, foliar disease identifications, weed detections, and leaf area coverage (Jarquin et al., 2018; Keller et al., 2018; Castelao Tetila et al., 2017; Yu et al., 2016). Continued investigations of phenotyping traits that are important for improving soybean cultivar

development against biotic and abiotic stresses within a double cropping production system can be explored using the UAV-based approach.

1.2.7 Breeding Improvement and Best Management Practices for Winter Barley. Due to the economic and environmental benefits of growing a cash winter malting crop, winter barley breeding efforts focused on improved winter hardiness have accelerated in the US and several winter two-row cultivars have been released in recent years (Windes and Obert 2009; Obert et al., 2009). In 2009, a winter malting barley breeding program was established at University of Minnesota (UMN), and is currently focused on developing two-rowed winter varieties. The target breeding environment for winter barley is in southern Minnesota, where the winter climate is not as harsh and where the possibility of double cropping exists. Thereafter, if sufficient and reliable winter hardiness is achieved in the breeding program, new breeding lines will be trialed in central and northern parts of the state.

Winter hardiness is a complex characteristic involving three primary traits: low temperature tolerance (LTT), photoperiod (PPD) sensitivity, and vernalization (VRN) sensitivity (Szűcs et al., 2007), and their pathways are highly interconnected (Muñoz-Amatriaín et al., 2010). Combining winter hardiness with acceptable malting characteristics remains a challenge (Muñoz-Amatriaín et al., 2010). Previous research indicated that there are many minor effect loci contributing to LTT (Chen et al., 2009a, 2009b; Falcon, 2016; Skinner et al., 2006). Genomic selection (GS) is especially appropriate for quantitative traits including winter hardiness. It incorporates all marker information in the prediction model, thereby avoiding biased marker effect estimates due to small-effect Quantitative Trait Loci (QTL) (Falcon, 2016; Heffner et al., 2009; Meuwissen et al., 2001). Previous GS results showed that the two traits that were most

crucial to the breeding goals of improved winter hardiness and malting extract were significantly improved in just two cycles of genomic selection (Falcon, 2016).

Field-scale winter survival evaluation is the most important indicator of winter hardiness for winter barley. Several environmental factors that contribute to winter survival include low temperatures, drought, flooding, soil heaving, ice encasement, desiccation, smothering, diseases and insects (Andrews, 1996; Andrews and Pomeroy, 1977). Cereal plants such as winter barley experience the most rapid change in LTT tolerance during initial stages of cold acclimation, which is an inducible process that occurs when plants are exposed to low non-freezing temperatures (Levitt, 1980). Once fully acclimated, cereals can maintain a high level of cold hardiness provided crown temperatures remain near or below freezing (Andrews and Pomeroy, 1977; Fowler et al., 2014; Gusta and Fowler, 1979). However, if plants are exposed to temperatures above the acclimation threshold, acquired LT will be rapidly lost (Fowler et al., 2014). The LT_{50} value, which refers to the temperature at which 50% of the population is killed in a controlled freeze test is used to quantify LTT (Fowler et al., 2014; Luo, 2011). Winter barley has been found to have an average LT_{50} value around -10°C (Kolar et al., 1991), but cultivars developed for cold environments such as the Upper Midwest may exhibit lower LT_{50} values.

Damage to the crown tissue was found to be another major factor for winter survival in most climates. Soil temperature at the crown depth is also critical to the acclimation process and winter survival for most winter cereal plants (Chen et al., 1983; Fowler et al., 2014). Crowns formed relatively deep are better protected against low temperature because of insulation provided by the soil (Dofing and Schmidt, 1985). In winter wheat, crown has been reported to be normally located less than two inches (5cm) below the soil surface (Fowler and Moats, 1995), and such depth may be relevant for winter barley.

Proteins are directly involved in plant stress response, and an additional research area that can contribute to a better understanding and improvement of cold stress expression is proteomics (Gołębiowska-Pikania et al., 2017). Although each barley plant contains the same set of genes, the set of proteins produced in different tissues of a barley plant can be different and dependent on gene expression (Guo et al., 2016). Proteomics complements genomics and is useful in identifying protein expression results based on responsive genes detected through genomics research (Eldakak et al., 2013).

At the proteome level, profound alterations in protein relative abundance levels have found between cold stressed and control plants and between differential genotypes of winter barley and winter wheat genotypes (Kosová et al., 2014). Comparative proteomic studies can contribute to the identification of novel proteins within a genotype or across various genotypes, and determine potential protein markers of the cold stress tolerance. Protein marker information, along with genome sequencing data could stimulate further research and applications in breeding for an improved cold stress tolerance in winter barley (Kosová et al., 2014). In winter wheat, it was noted that field evaluation of winter survival is often not an ideal measure of cold tolerance due to inconsistent evaluations of test winters that may allow for the detection of winter hardiness variations among genotypes (Fowler and Gusta 1979). Breeding lines that exhibit various levels of winter hardiness may be detected by drawing correlations between responsive genes and observed stress tolerance phenotypes through a combination of genomics and proteomics research without evaluating any field trials.

Timely planting is a key component for successful winter barley production (Culman et al., 2017). Winter barley can be grown in various regions in the US between September to November. In the New England area such as in Vermont, the third week of September to early

October planting date has been recommended for winter barley planting date (Darby et al., 2017; Wise et al., 2016). In the Ohio Valley region, planting is recommended after the Hessian fly (*Mayetiola destructor*)–safe date (Culman et al., 2017), and this date typically falls on the third week of September (Shrestha and Lindsey, 2019). The Hessian fly–safe date coincides with reduced numbers of adult aphids (*Aphis* spp.), which can transmit barley yellow dwarf virus to seedlings in the autumn (Paul and Hammond, 2010). In Michigan, it was observed that winter barley planted by mid-September resulted in higher yield and lower grain protein (McFarland et al., 2014).

Input requirements, particularly nitrogen, are relatively low for winter barley. Therefore, this crop is typically grown under moderate nitrogen fertility conditions because high fertility will reduce kernel plumpness, increase lodging, and exceed the kernel protein threshold preferred by brewers (Culman et al., 2017; Shrestha and Lindsey, 2019). In determining the appropriate nitrogen fertilizer levels, the grain protein target for malting barley is between 11.5% and 13% (Mahler and O. Guy, 2007). Compared to winter wheat, winter barley requires fewer fungicide sprays and fertilizer inputs (Mahler and O. Guy, 2007). In such a respect, it is a lower input crop, helping to reduce the overall production cost and easing cash-flows.

Further research to examine other agronomic management practices such as planting density, row spacing, and fertility management will be crucial to the successful production of winter barley. While breeders will continue to develop winter barley varieties that can consistently survive and thrive under winter conditions in Minnesota, producers should do everything they can to plant at the proper time, depth, and in better drained fields to increase the chances of winter survival (Verbeten et al., 2014).

1.3 Assessment of a Winter Barley-Soybean Double Cropping System

1.3.1 Stakeholder Engagement towards New Crop and Cropping System Development.

Introduction of new crops into existing agricultural systems may offer significant environmental and economic benefits to many potential stakeholders involved in the malting barley supply chain. An agri-food supply chain involves processes from the agricultural production of raw ingredients to the delivery of final products to the consumer, and each step in the entire production system is viewed as link in the chain (Leat P and Revoredo-Giha C, 2014; Smith, 2008). Stakeholders are groups and individuals that are influential or are influenced by an organization that could be a part of an supply chain (Parmar et al., 2010). Agriculture is inherently a fragmented industry involving a diverse range of distinct stakeholders (farmers, processors, marketers, and distributors) (Smith, 2008). Important stakeholders involved in a potential winter barley supply chain may include growers, maltsters, and brewers.

Optimizing the entire supply chain will require an extensive amount of information sharing, teamwork, cooperation and collaboration among the participating stakeholders (Leat P and Revoredo-Giha C, 2014; Smith, 2008). Therefore, stakeholder engagement will be critical for a new crop or cropping system development as it is as important to the on-going breeding and production research. Such engagement could improve both the relevance of research to stakeholder interests and needs, and the public understanding of these systems with their social, environmental, and management trade-offs (Robertson et al., 2008). Acquiring multi-stakeholder perceptions of a new crop and cropping system is even more important because these perceptions could capture the diversity of societal values, voices, and beliefs on a topic brought by many stakeholders involved (Peterson, 2013). Evaluating and characterizing these perceptions could help to further facilitate and encourage more stakeholders to become aware and possibly collaborate on potential activities that could link upstream farming systems developed by

researchers and farmers with downstream markets and consumers utilizing the crop and related-products (Meynard et al., 2017).

1.3.2 Interview Research Methodology for Understanding Stakeholder Perceptions.

Interview presents an effective approach to determine the perceptions of stakeholders in regards to new cropping systems. Adebisi et al., (2015) conducted interviews on the perceptions for perennial wheat among 11 farmers from Michigan and Ohio. Perennial wheat was not yet commercially available for production in these states, and semi-structured interviews were conducted to allow for in-depth discussions of the crop's potential characteristics and uses (Adebisi et al., 2016). Through these interviews, farmers shared 10 different end-uses for perennial wheat. In another study, 15 rural landowners in the Upper Sangamon River Watershed of Central Illinois were interviewed for their design preferences, information needs, and the adoption potential for Multifunctional woody polycultures (MWPs) (Stanek et al., 2019). MWPs serve as an option for combining agricultural production and conservation goals. Results of this study revealed that a lack of reliable economic, marketing, and management information could severely impede the adoption potential of MWPs. Diverse responses and interests stimulated from an interview research project are extremely valuable for new crop development and its eventual commercialization. These *ex ante* studies were able to gauge interests and potential uses of various new crops among farmers. A semi-structured interview is the most widely used interviewing format for qualitative research, and can allow researchers to gain insight into stakeholder decision making around the adoption of a new technology, crop production system, or end-use application (DiCicco-Bloom and Crabtree, 2006). Thus, this type of interview methodology may serve as one critical step in addressing the numerous challenges towards the development of more diversified and sustainable agricultural systems.

594 Table 1-1. Outline of soybean double cropping studies in the Upper Midwest (2010-2018)

Study	Location	Crops paired with soybean	Treatment investigated	Soybean planting date	Full- season Soybean MG	Double cropping Soybean MG
Gesch et al. (2013)	Morris, MN (45°35'N)	Winter camelina	Yield and production costs	6/26- 7/1	MG II	MG 0.6
Gesch et al. (2014)	Morris, MN (45°35'N)	Winter camelina	Yield, economic returns, and energy efficiency	6/30- 7/11	MG 00	MG I
Berti et al. (2015)	Prosper, ND (46°58'N), Carrington, ND (47°30'N), and Morris, MN (45°35'N)	Winter Camelina (Camelina sativa L.)	yields, seed quality, economics, and within-field energy balance	7/5-7/11	MG 0.7	MG 0.1
Johnson et al. (2015)	Rosemount, MN (44°43'N), Waseca, MN (44°04' N), and Lamberton, MN (44°14' N)	Field pennycress	Yield	6/11	N/A	MG I
Johnson et al. (2017)	Rosemount, MN (44°43'N), Waseca, MN (44°04' N), and St. Paul, MN (44°59' N)	Field pennycress (Thlaspi arvense L.) and winter camelina	Yield and inorganic soil N	7/7-7/8 7/1-7/15	MG II	MG I

595

596

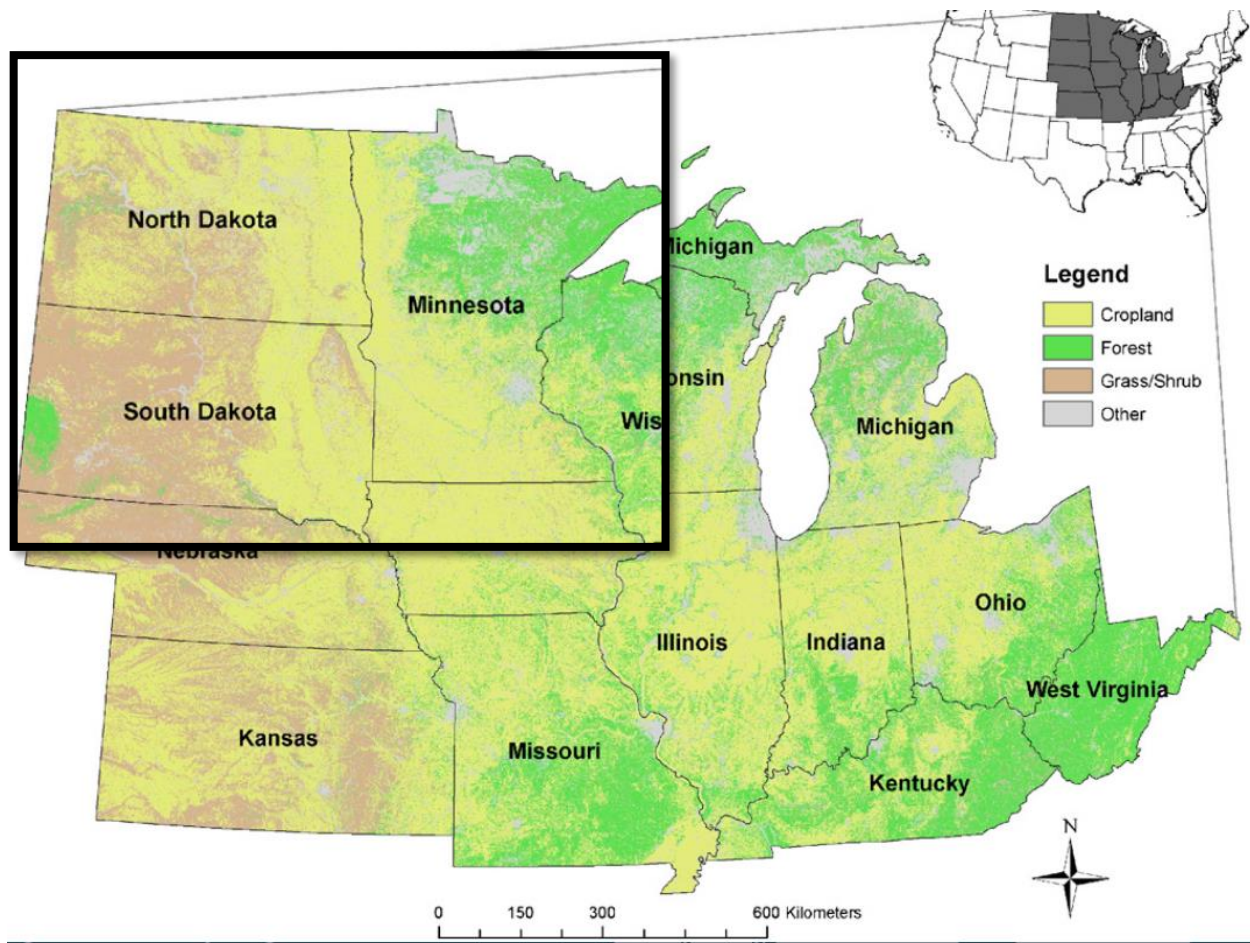


Figure 1-1. Map of the Midwest emphasizing the Upper Midwest (Maxwell et al., 2008).

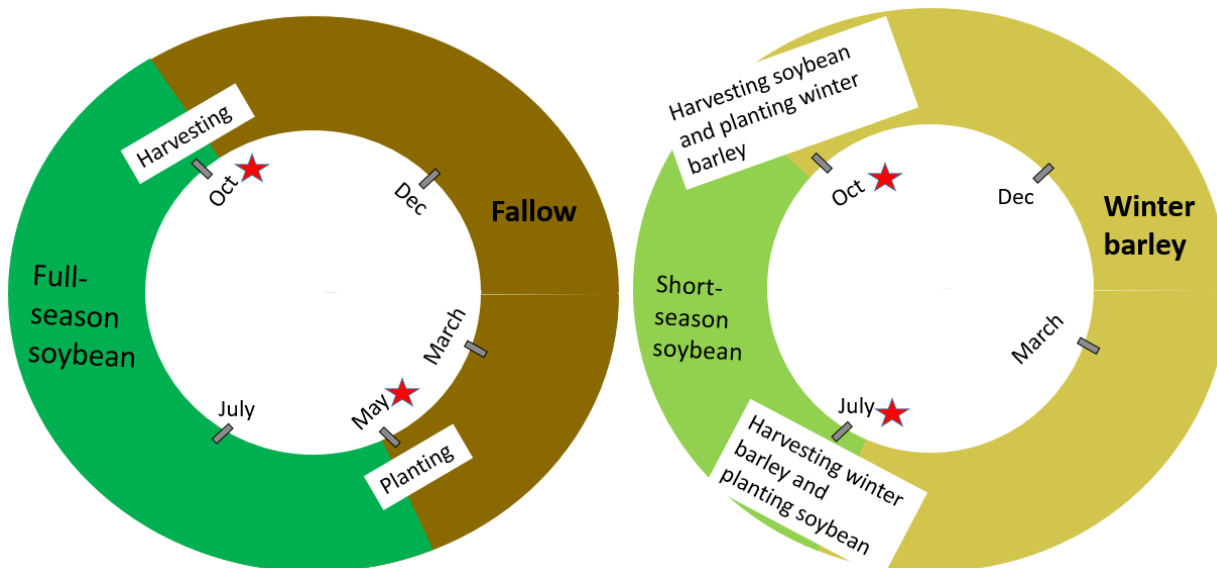


Figure 1-2. Illustration of the monocropping soybean production system (left), and a potential winter barley-soybean double cropping system in Minnesota (right). Stars highlight the planting and harvesting time for each crop.

**CHAPTER 2: ASSESSMENT OF WINTER BARLEY IN MINNESOTA:
RELATIONSHIPS AMONG CULTIVAR, FALL SEEDING DATE, WINTER
SURVIVAL, AND GRAIN YIELD**

**This chapter is a draft of a manuscript that has been accepted to a peer-reviewed journal
with the following authors:**

Becky H. Zhong*, Jochum J. Wiersma, Craig C. Sheaffer, Brian J. Steffenson, and Kevin P.
Smith

Author Affiliations: Becky H. Zhong, Craig C. Sheaffer, and Kevin P. Smith, Dep. of
Agronomy and Plant Genetics, University of Minnesota., St. Paul, MN 55108; Jochum J.
Wiersma, Dep. of Agronomy and Plant Genetics, University of Minnesota, Crookston, MN
56716; Brian J. Steffenson, Dep. of Plant Pathology, University of Minnesota., St. Paul, MN
55108. *Corresponding author (zhong287@umn.edu).

2.1 Synopsis. Winter barley (*Hordeum vulgare* L.) is currently being developed as a new cash
crop with potential to provide both economic and environmental benefits in Minnesota. In a field
experiment, three winter barley cultivars that exhibited different levels of winter hardiness were
sown at four planting dates (early September to mid-October with a ~2-week interval between
each planting date) in St. Paul from 2010-2013 and 2015-2018, and in Lamberton from 2015-
2019. Fall growing-degree-days (GDD), winter snow coverage, winter survival, and grain yield
were evaluated across eleven site-years. Only 55% of site-years had a winter survival at 20% or
greater when averaged across all planting dates and cultivars. No specific planting date
consistently resulted in maximum winter survival. McGregor, a non-malting barley had the
highest winter survival and yield. Planting dates that resulted in fall accumulated GDD from 600

to 1400 were associated with better winter survival in years with sufficient snow cover. Less than four inches of snow cover and temperatures at or below -4°F for more than three days led to poor winter survival in five of the eleven site-years. Continued breeding for improved winter hardiness and agronomic research that provides best management practices will be needed to develop a practical winter barley cropping system for Minnesota.

2.2 Introduction. Winter annual cover crops such as winter cereal rye (*Secale cereal* l.) improve soil structure and enhance water infiltration following the harvest of summer annual grain crops (Kaspar et al., 2012; Mitchell et al., 2013). Currently, there is limited economic return from cover crops grown in the Upper Midwest (Singer et al., 2007; Roesch-Mcnally et al., 2017). Winter barley (*Hordeum vulgare* L.) may potentially offer several advantages if grown as a winter cash crop in Minnesota. When planted in Netherlands, winter barley produced more shoots per meter and a greater harvest index compared to winter wheat and rye (Ellen, 1993). In the US, winter barley is typically harvested five to ten days earlier than winter wheat (*Triticum Aestivum* L.) in states such as Pennsylvania (Usda National Agricultural Statistics Services, 2010). Harvesting earlier than winter wheat may allow winter barley to fit in a double cropping or intercropping system with a summer annual cash crop such as soybean (Camper et al., 1972; Knapp And Knapp, 1980). When comparing with winter wheat, winter barley produced more grain yield per unit of applied N (Delogu et al., 1998). As a result, the lowered N requirement makes winter barley a better choice to reduce ground-water pollution due to nitrate leaching during the winter and early spring. In addition, winter barley is garnering increased attention as a source of malt for the expanding craft brewing industry (Brouwer et al., 2016; Kaufenberg, 2017). In New York, the farm brewery license program incentivizes farm breweries to source 20% of their ingredients locally when making malted beverages, and this percentage

will increase to 90% by 2024 (Stempel, 2016; Hmielowski, 2017). Winter barley that meets malting standards could potentially fulfill this market demand (Hayes et al., 2012; Culman et al., 2017).

The extent to which winter barley can provide both economic and environmental benefits depends on its ability to survive the winter and produce sufficient yield of high quality grain. Winter survival is a highly complex trait that is the result of multiple environmental stressors (Gray et al., 1997; Bergjord Olsen et al., 2018). Harsh winter conditions including sub-freezing temperatures can reduce plant survival. In colder climates, snow can insulate plants from extremely low and fluctuating temperatures (Aase and Siddoway, 1979). However, weather conditions and snow cover can vary significantly within each production zone in Minnesota and may create uncertainty as to whether winter barley will consistently survive (Daly et al., 2012). Planting date can influence winter survival and grain yield for winter cereal crops (Jedel and Salmon, 1994; Nleya and Rickertsen, 2014). Recommended planting dates for winter wheat have been established for different regions of Minnesota (Wiersma, 2006), but not for winter barley. The objectives of this study were to evaluate the effect of planting date, cultivar, fall growth, and winter weather on winter barley survival.

2.3 Field Experiments and Treatment Description. Field experiments were fall-sown at St. Paul, MN (44.99° N, 93.18° W) in 2010-2012 and 2015-2017 and Lamberton, MN (44.24° N, 95.31° W) in 2015-2018. Winter survival was assessed in all eleven site-years. Severe winterkill (lower than 20% survival) was observed in five of the eleven site-years, and grain yield was assessed in trials planted in 2010, 2011, 2015, and 2017 at St. Paul, and in 2015 at Lamberton. The soil type at St. Paul is a Waukegan loam (fine-silty over sandy or sandy-skeletal, mixed,

superactive, mesic Typic Hapludolls), and the soil type at Lamberton is a Normania loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls).

Previous crops were buckwheat (*Fagopyrum esculentum* Moench) at St. Paul and oats (*Avena sativa* L.) at Lamberton. The buckwheat crop was mowed and incorporated as a green manure, and the oat was harvested and stubble remained. Prior to planting, fields at St. Paul were disked, fertilized with 17 lb N acre⁻¹ and field cultivated, with no fertilizer applied in the spring. Oats were swathed at soft dough stage, combined, and straw was removed with a round baler at Lamberton prior to winter barley planting. No fertilizer was applied in the fall, and 85 lbs acre⁻¹ of fertilizer N was applied as urea in the spring at Lamberton. The experimental design was a randomized complete block with four replications in 2010-2013 at St. Paul, six replications in 2015-2017 at St. Paul, and six replications in 2015-2019 at Lamberton. Treatments were arranged in a split plot design, with planting date as the main plot, and winter barley cultivar as the subplot. Three barley cultivars exhibiting different winter hardiness levels (low to high), row type (two-row and six-row), growth habit (winter or facultative) and end-use (malting and feed) were used in the study (Table 2-1). Four planting date treatments were evaluated: September 1, September 15, October 1, and October 15 for each site-year; however, the actual planting date varied (Table 2-2). During each planting date, barley was drilled in rows (7-inch spacing) at a depth of 0.75 inch in 5- by 15-ft plots with a rate of 25 seeds sq ft⁻¹ using a ten-row Almaco cone planter (Almaco, Nevada, IA) at St. Paul, and a no-till Marliss grain drill (Remlinger Manufacturing Company, Inc., Kalida, OH) at Lamberton.

2.4 Data Collection and Analysis. Stand count was evaluated in late October and in May by counting the number of living plants present in one 40 inch segment in two different rows per plot. Percent winter survival was calculated by dividing the stand count in the spring by the stand

count in the fall and multiplying by 100. Grain yield was measured by harvesting a 3.5- by 12-ft area within each plot using a Wintersteiger plot combine (Wintersteiger Ag, Ried im Innkreis, Austria) in late June to early July after all treatments had reached physiological maturity. Harvested grain samples were dried at 80°F for 10 days in a forced air dryer, and grain yields were adjusted to a constant moisture of 14% and expressed as bu acre⁻¹.

Weather observations that included daily minimum and maximum air temperature, snow depth, and precipitation from September 1 to July 1 at the two sites were obtained using the *RNOAA* package in R (Chamberlain, 2017). The fall freeze date was considered the date when five consecutive days of moving average temperature dropped below 32°F (Andrews et al., 1997). Daily observation of Growing Degree Days (GDD) were calculated from planting date to the freeze date in the fall using the barley growth estimation from air temperature (Bauer et al., 1993), with a $T_{BASE} = 32^{\circ}\text{F}$, a $T_{MAX} = 70^{\circ}\text{F}$ prior to Haun stage 2.0, and a $T_{MAX} = 95^{\circ}\text{F}$ after Haun stage 2.0 (Haun, 1973; Bauer et al., 1993). Two minimum temperature thresholds (14°F and -4°F) representing the lethal temperatures (LT_{50}) for winter barley and winter wheat (Kolar et al., 1991; Fowler et al., 2014), and a snow depth threshold of four inches or more were used as a benchmark for predicting plant survival.

Initial analysis of variance was conducted in R 3.5.2 (R Core Team, 2018) using the *lmer* package (Kuznetsova et al., 2017) with site, planting date and cultivar as fixed effects, and year, block, and interactions involving year and block considered random effects. These analyses indicated strongly significant ($P \leq 0.05$) treatment by site-year interactions. Consequently, each site-year was analyzed separately using the *lm* function in R, and within each site-year, treatments were modeled as fixed effects, and blocks as random effects. When the F-test was significant, a mean separation test was conducted using Fisher's protected LSD. Due to low

winter survival and poor grain yield for Charles and Maja in many of the site-years, analysis of grain yield was only conducted for McGregor. The *lm* function in R was used for all regression analyses to model the effect of planting date on winter survival and winter survival on grain yield.

2.5 Results and Discussions.

2.5.1 Environmental Conditions. Growing conditions with respect to temperature and snow cover were different in each site-year (Figure 2-1 and 2-2). The lowest fall precipitation occurred during 2011-2012 at St. Paul (2.79 inches), and the highest precipitation occurred in 2015-2016 at St. Paul (10.16 inches). Fall temperatures were similar in all the site-years, but winter conditions were drastically different from site-year to site-year. Extremely cold temperatures below -22°F were recorded in 2010-2011 and 2017-2018 at St. Paul, and in 2018-2019 at Lamberton. The greatest snow depth was recorded in 2018-2019 at Lamberton (29 inches), and the lowest snow depth in 2011-2012 (0.30 inch) at St. Paul. In the spring, dry conditions were again observed in 2010-2012 at St. Paul and in 2015-2016 at Lamberton, while more precipitation events occurred in the other site-years.

2.5.2 Planting Date and Cultivar Effects on Winter Survival. Five out of eleven site-years had poor winter survival with less than 20% survival for all planting dates and cultivars. Winter survival observed at the other six site-years (> 20% survival) greatly depended on planting date and cultivar. Planting date significantly affected winter hardiness in these six site-years, except in 2015-2016 at Lamberton (Table 2-3). The relationship between planting date and winter survival is shown in Fig. 1 and 2. No consistent planting window was identified that maximized winter survival among any of the site-years. Winter survival showed linear relationships to planting date in 2011-2012 at St. Paul and in 2018-2019 at Lamberton, and quadratic

relationships in 2015-2016 and 2017-2018 at St. Paul. The other two site-years showed no relationship of planting date to winter survival.

A significant interaction occurred between planting date and cultivar for winter survival at all the six site-years with substantial winter survival, except at St. Paul from 2015-2016 (Table 3). Regression analysis of planting date on winter survival showed that quadratic or linear models best described the relationship of planting date to winter survival, except for Charles and Maja in 2010-2011 at St. Paul, and Maja in 2015-2016 at Lamberton.

2.5.3 Effect of Fall Growth on Winter Survival. One key factor that can influence winter survival is fall GDD. In the present study, diverse weather conditions in each site-year produced a wide range (43 – 1831) of accumulated GDD for the planting date treatments (Table 2-4). Planting around Sept 1 resulted in higher GDD, but led to poor winter survival in 2010-2011 (1819) and 2011-2012 at St. Paul (1620). Excessive GDD may lead to growth beyond the ideal winter acclimation condition and negatively impact winter survival (Vico et al., 2014). In addition, lower winter survival for early planting dates may be attributed to increased exposure to diseases such as barley yellow dwarf virus (McGrath and Bale, 1990; Nleya and Rickertsen, 2014). In contrast, late planting may not allow the plant to achieve an adequate hardening level before winter or to store sufficient resources for growth and development in the spring (Andrews et al., 1997; Hall, 2012). Planting late around Oct 1 and Oct 15 in 2017-2018 at St. Paul generated 325 and 43 GDD, respectively, and produced poor winter survival. Despite the fact that we could not identify a specific planting window date, planting that results in sufficient GDD and reduces exposure to disease should provide the best opportunity for winter survival.

2.5.4 Effect of Winter Weather Conditions on Winter Survival. In cold climates, snow cover is critical for winter survival of winter cereal crops, because it insulates the soil and provides

protection to the crown tissue of plants during cold winter conditions (Heard and Domitruk, 2001; Fowler et al., 2014). A minimum of four inches of trapped snow cover from December to early March is recommended for winter wheat production in cold environments such as Manitoba, Canada. Similar conditions may apply to winter barley production in Minnesota (Fowler and Moats, 1995; Struthers and Greer, 2001). In the present study, cold temperatures at or below -4°F without snow cover were critical factors in the survival of winter barley (Table 2-5). The five site-years (2012-2013 and 2016-2017 at St. Paul and from 2016-2019 at Lamberton) with poor winter survival had greater than four days of minimum temperature at or below -4°F without any snow cover. In contrast, the six site-years with better winter survival had fewer than four days of no snow cover at or below -4°F. Interestingly, all of the eleven site-years had multiple days without snow cover at or below 14°F, suggesting the LT₅₀ for winter barley may actually be lower than 14°F.

Previous crop management can greatly enhance trapped snow coverage. For example, planting winter wheat into standing crop residues such as canola (*Brassica napus* L.) and spring barley have been shown to provide sufficient trapped snow (Fowler and Moats, 1995). Standing stubble also contributes to reduce the chance of breaking winter dormancy during early spring or a mid-winter thaw for winter wheat (Wiersma, 2006). In the present study, stubble was not present in any site-years at St. Paul, so preserving stubble could have increased winter survival. Further research will be necessary to determine ideal summer crops to plant prior to winter barley to enhance its winter survivability.

2.5.5 Effect of Winter Survival on Grain Yield. McGregor had the highest winter survival across all the site-years and planting dates, averaging 59% compared to 41% and 42% for Charles and Maja, respectively (Table 2-6). Winter survival for McGregor at the five site-years

where >20% average winter survival was observed was positively associated with yield and fit a quadratic response (Figure 2-3). The correlation coefficients for the quadratic regression were significantly ($P < 0.05$) ranging from 0.26 to 0.83 (Table 2-7). In four of the five site-years, we observed that yield maximized in a range of winter survival from 64% to 93%. These inconsistent responses did not allow us to predict the optimal winter survival rate for maximized grain yield.

2.5.6 Future Outlook of Winter Barley Production in Minnesota. Although many studies have reported the relationship of planting date to winter survival and grain yield for other winter cereal crops (Knapp and Knapp, 1980; Jedel and Salmon, 1994; Sacks et al., 2010; Hall, 2012), this is the first study to examine the relationship of cultivars and planting dates to winter survival and yield for winter barley. Reliable and sustainable winter barley production in cold climates will require cultivars with substantially better winter hardiness than is currently available. Moreover, management practices such as retaining crop stubble to increase snow catch should be utilized to improve winter survival and yield (Verbeten et al., 2014). An ideal winter barley cultivar for cash crop production in Minnesota will need to possess sufficient malting quality to capture premium value from the malting and brewing industries. McGregor had the highest winter survival among the three cultivars tested, but it is a feed grade barley. Continued breeding and additional management studies will be needed to produce the resources for growers to realize the potential of growing winter barley.

829 Table 2-1. Winter barley cultivars evaluated for winter survival for ten site-years at St. Paul (STP)
 830 and Lamberton (LAM), Minnesota.

Cultivar	Origin	Year of Release	Growth habit /spike type	End-use purpose	Winter Hardiness Rating
Charles	Aberdeen, ID	2005	Winter two-row	Malt	Low to medium
Maja	Corvallis, OR	2006	Facultative six-row	Malt/Feed	Low to medium
McGregor	Unknown	1995	Winter six-row	Feed	Medium to high

831

832

833

834

835 Table 2-2. Targeted and actual planting dates used in evaluating the winter survival for ten site-
 836 years at St. Paul (STP) and Lamberton (LAM), Minnesota.

Site-year	2010	2011	2012	2015	2015	2016	2016	2017	2017	2018
	STP	STP	STP	STP	LAM	STP	LAM	STP	LAM	LAM
Targeted planting date	Actual planting date									
1 Sept.	26 Aug.	31 Aug.	6 Sept.†	9 Sept.	4 Sept.	1 Sept.†	2 Sept.†	6 Sept.	1 Sept.†	30 Aug.
15 Sept.	9 Sept.	15 Sept.	18 Sept.†	22 Sept.	18 Sept.	15 Sept.†	14 Sept.†	19 Sept.	14 Sept.†	14 Sept.
1 Oct.	22 Sept.	29 Sept.	3 Oct. †	29 Sept.	2 Oct.	29 Sept.†	29 Sept.†	10 Oct.	30 Sept.†	28 Sept.
15 Oct.	6 Oct.	11 Oct.	23 Oct.†	13 Oct.	16 Oct.	11 Oct.†	14 Oct.†	25 Oct.†	13 Oct.†	17 Oct.

†Planting dates resulting in lower than 20% winter survival across all cultivars.

837

838

839

840

841 Table 2-3. Effect of planting date and cultivar treatments on winter barley survival in four growing seasons at St. Paul and two at
842 Lamberton, MN.

Source	St. Paul 2010-2011	St. Paul 2011-2012	St. Paul 2015-2016	Lamberton 2015-2016	St. Paul 2017-2018	Lamberton 2018-2019
Planting Date (PD)	0.0431	<0.0001	<0.0001	0.0650	<0.0001	<0.0001
Cultivar (C)	0.0004	0.0004	<0.0001	0.0133	0.0071	0.1099
PD x C	0.0038	0.0090	0.6487	0.0148	0.0085	0.0101
<u>Contrasts by planting dates</u>						
Charles						
Linear	0.1358	0.0097	N/A±	0.0202	<0.0001	<0.0001
Quadratic	0.3272	0.2956	N/A±	0.2162	<0.0001	<0.0001
Maja						
Linear	0.1492	<0.0001	N/A±	0.2280	<0.0001	0.0205
Quadratic	0.3442	0.1940	N/A±	0.1290	<0.0001	0.1463
McGregor						
Linear	0.0460	<0.0001	N/A±	0.6180	<0.0001	0.0019
Quadratic	0.0629	0.0299	N/A±	0.0248	0.0008	0.0500

843 ± Contrast analysis was not conducted due to insignificant PD x C interaction effect.

844
845
846
847
848
849
850
851
852
853
854
855
856
857
858
859

860 Table 2-4. Accumulated growing degree days (GDD) °F (base=32) from actual planting date to freeze-up date for four target planting
861 date treatments used in the evaluation of the winter survival of winter barley cultivars for ten-site years at St. Paul and Lamberton,
862 Minnesota.

	Target Planting Dates				Freeze-up date ^y
	1 Sept.	15 Sept.	1 Oct	15 Oct	
<i>St. Paul</i>					
2010	1819	1339	997	683	14 Nov.
2011	1620	1151	850	515	27 Nov.
2012	1696	1266	834	469	2 Dec.
2015	1464	1100	877	588	20 Nov.
2016	1768	1359	933	667	20 Nov.
2017	1250	758	325	43	5 Nov.
Mean‡	1358	1087	908	595	
<i>Lamberton</i>					
2015	1802	1286	855	539	20 Nov.
2016	1831	1414	943	642	6 Dec.
2017	1634	1207	693	429	5 Dec.
2018	1414	838	417	213	8 Nov.
Mean‡	1802	1286	855	539	

863 Bolded values indicate dates with >20% winter survival winter survival.

864 ^yFreeze-up date estimated as date at which the 5-d moving mean of daily mean temperatures dropped below 32°F.

865 Table 2-5. Number of days with a lack of sufficient snow coverage in St. Paul from 2010-2013, and 2015-2018, and Lamberton from
866 2015-2018.

Site-year	Days of minimum temperature below -4°F without snow cover	Days of minimum temperature below 14°F without snow cover	winter survival >50% observed for one or more planting dates
St. Paul 2010-2011	0	8	Yes
St. Paul 2011-2012	2	32	Yes
St. Paul 2012-2013	6	21	No
St. Paul 2015-2016	0	7	Yes
St. Paul 2016-2017	6	26	No
St. Paul 2017-2018	3	19	Yes
Lamberton 2015-2016	0	10	Yes
Lamberton 2016-2017	5	27	No
Lamberton 2017-2018	21	52	No
Lamberton 2018-2019	4	17	No

867
868
869
870
871
872
873
874
875
876
877
878
879
880

881

882
883
884

885

886 Table 2-6. Percent winter survival for three winter barley cultivars at each target planting date for three growing seasons at St. Paul
887 and one at Lamberton, MN.

Planting date and cultivar treatment±	St. Paul 2010-2011	St. Paul 2011-2012	St. Paul 2015-2016	Lamberton 2015-2016	St. Paul 2017-2018	Lamberton 2018-2019
1 Sept.						
Charles	4.0b±	3.0a	75.0b	71.7b	7.5b	77.9 a
Maja	11.3b	0.0a	71.7b	75.0b	26.0a	30.8 ab
McGregor	62.5a	12.8a	86.7a	86.7a	29.3a	72.9 a
15 Sept.						
Charles	13.8a	11.3b	81.7b	81.7b	62.5ab	36.2 b
Maja	21.3a	0.5b	76.7b	76.7b	54.2b	41.3 a
McGregor	28.75a	35.8a	90.0a	90.0a	73.3a	54.5 ab
1 Oct.						
Charles	21.3b	31.8b	90.0b	90.0b	6.5a	26.2 b
Maja	22.5b	38.8b	86.7b	86.7b	18.8a	23.8 ab
McGregor	55.00a	78.0a	100.0a	100.0a	15.0a	38.7 ab
15 Oct.						
Charles	20.0b	27.0c	65.0b	65.0b	1.7a	22.1 b
Maja	42.5a	54.5b	68.3b	68.3b	6.8a	16.3 b
McGregor	47.5a	75.0a	78.3a	78.3a	4.7a	26.2 b

888 ± Means followed by the same letter are not significantly different based on Fisher's Protected LSD test at $p < 0.05$ within columns and by planting date

889

890

891

892 Table 2-7. Effect of planting dates (day of the year) on grain yield of winter barley cultivar McGregor for five site-years.

Site-year	Regression Equation†	R ²
	<u>Grain yield</u>	
2010-2011 STP	yield (bu acre ⁻¹) = -1953.72+233.93x-1.4x ²	0.65***
2011-2012 STP	yield (bu acre ⁻¹) = 509.67+76.81x-0.44x ²	0.76***
2015-2016 STP	yield (bu acre ⁻¹) = 10680.25-217.11x+1.45x ²	0.55***
2015-2016 LAM	yield (bu acre ⁻¹) = -2628.41+140.61x-0.60x ²	0.26*
2017-2018 STP	yield (bu acre ⁻¹) = 67.32-6.73x-+0.43x ²	0.83***

893 † x, day of the year.

894 *, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

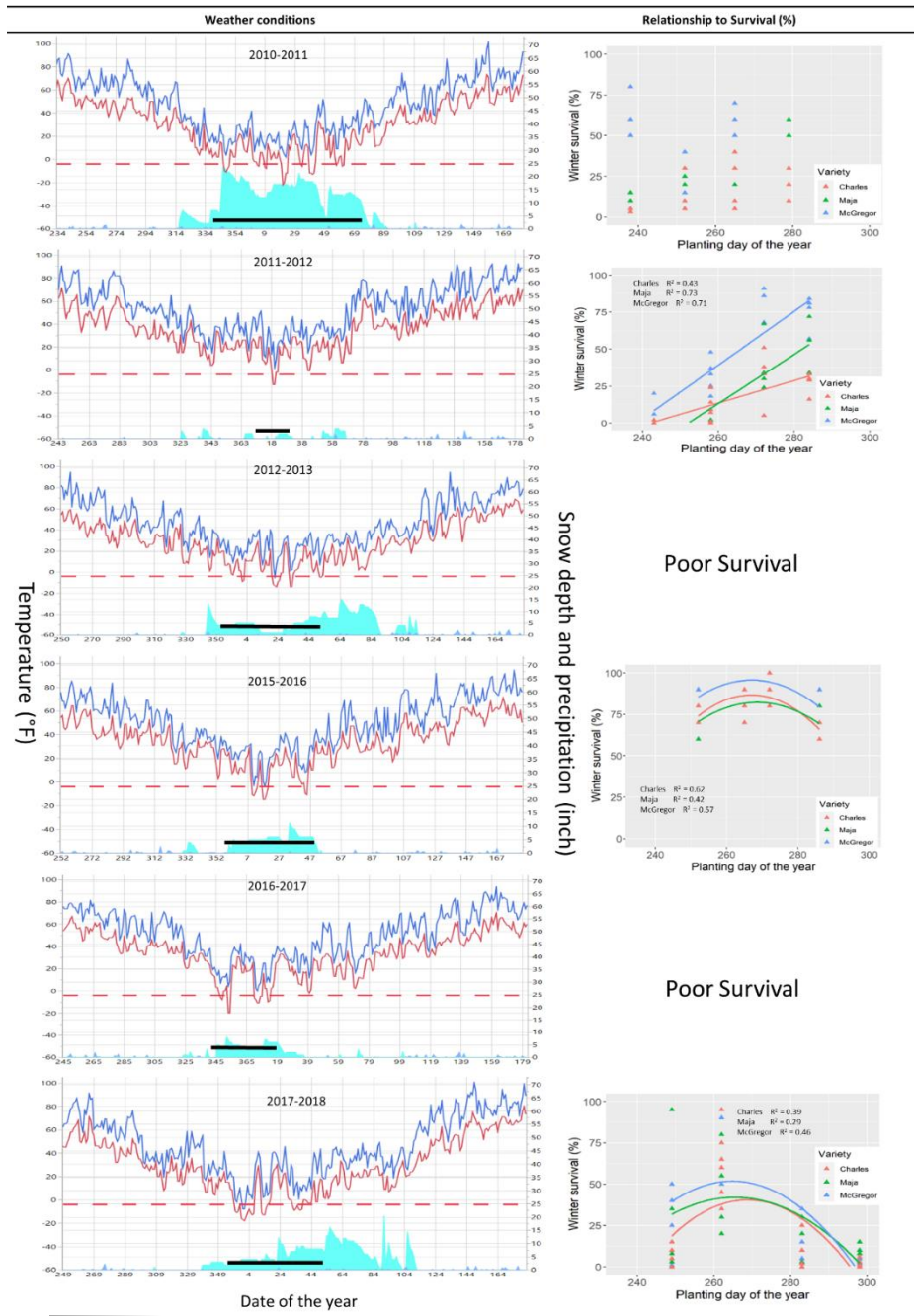


Figure 2-1. Maximum temperature per day (blue line), minimum temperature per day (red line), snow depth per day (light blue area), and precipitation per day (dark blue area), presence of four inches of snow depth when minimum temperature is at or below -4°F (black line), and regression analysis of planting date to winter survival 2010-2013 and 2015-2018 at St. Paul, MN.

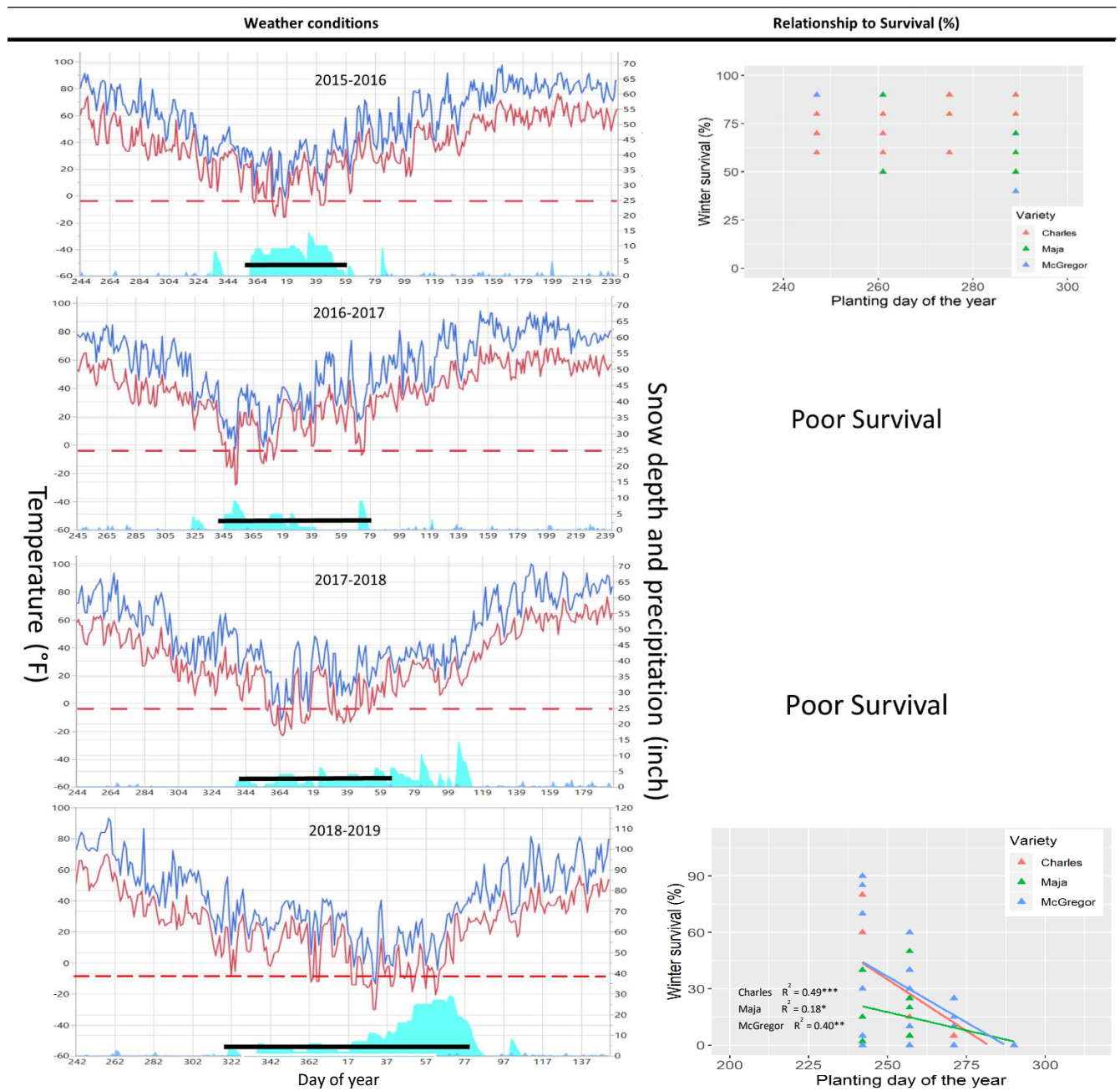


Figure 2-2. Weather conditions include maximum temperature per day (blue line), minimum temperature per day (red line), snow depth per day (light blue area), and precipitation per day (dark blue area), presence of four inches of snow depth when minimum temperature is at or below -4°F (black line), and regression analysis of planting date to winter survival during 2015-2018 at Lamberton, MN.

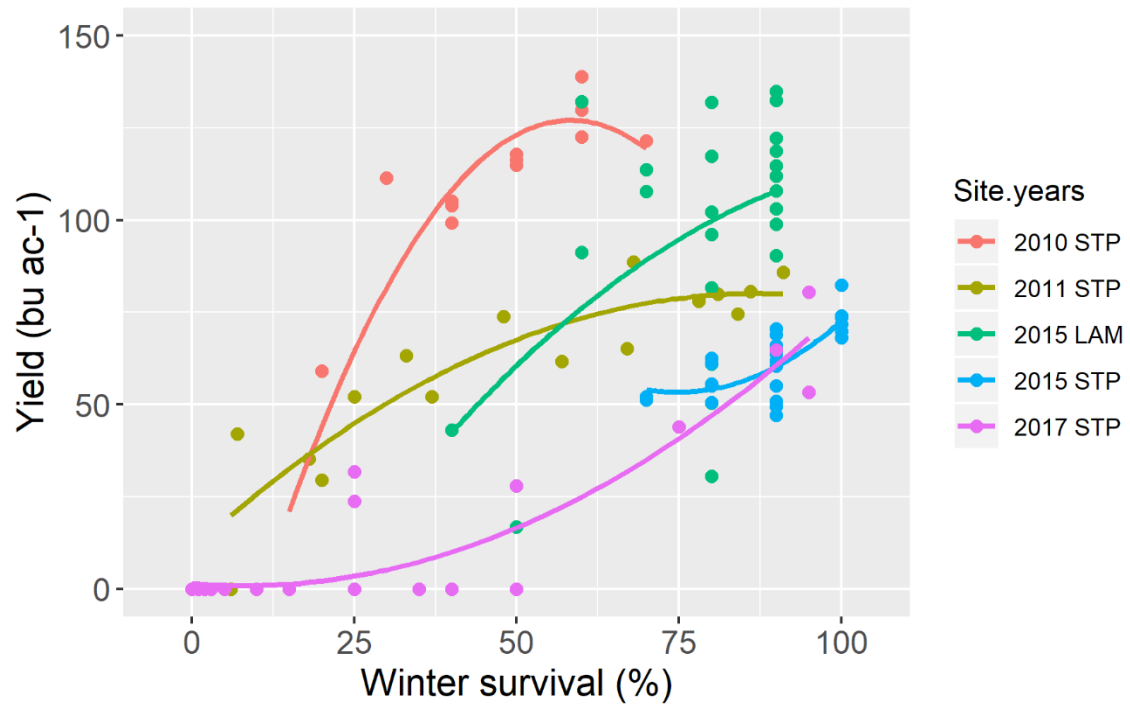


Figure 2-3. Relationship between winter survival and grain yield for the cultivar McGregor at five site-years with greater than 20% average winter survival. Each point represents a plot at each site-year.

CHAPTER 3: DIVERSIFYING SOYBEAN-BASED CROPPING SYSTEMS: EXPLORING CULTIVAR x ENVIRONMENT INTERACTIONS FOR DOUBLE CROPPING SOYBEANS IN THE UPPER MIDWEST

3.1 Introduction. Soybean (*Glycine max* L.) is the largest oilseed crop produced in the US, and over 80% of soybeans are currently produced in the Upper Midwest (National Agricultural Statistics Service, 2018). It is estimated that nearly 98% of soybeans are produced within a full-season (FS) production systems in the Midwest (Borchers et al., 2014), meaning that only a single soybean crop is produced during a growing season each year (Dillon, 2014). Winter cover crops such as winter rye (*Secale cereale* L.), hairy vetch (*Vicia villosa* Roth), clover (*Trifolium* L.), and forage radish (*Raphanus sativus* L. var. *longipinnatus*) may be planted following the harvest of FS soybeans to increase crop diversity; as well as enhance ecosystem services, and improve soil-water infiltration, organic matter, and soil structure (Berti et al., 2017; Hartwig and Ammon, 2002). Reduced soil erosion is also a benefit of planting winter cover crops (Kaspar et al., 2001). However, many growers are deterred from growing a cover crop due to its lack of economic return (Roesch-McNally et al., 2017; SARE CTIC, 2017). One solution to mitigate this challenge is to incorporate short-season (SS) soybean with a winter annual cash crop such as winter barley, pennycress, and camelina in a double or inter cropping system that can produce two cash crops in one year within the same field (Eberle et al., 2015; Gesch et al., 2014; Johnson et al., 2017, Zhong et al., unpublished). The SS soybean-winter annual system holds potential to increase overall production without expanding land area and the net return for growers by generating a winter cash crop in addition to soybean, and to aid in sustainably intensifying farming systems (Crabtree et al., 1990; Hansel et al., 2019; Kyei-Boahen and Zhang, 2006).

The growing environment, including solar radiation, temperature and water availability for SS soybeans is drastically different from FS soybeans. In addition, soybean is highly sensitive to regional temperature and day-length effects (Dong et al., 2004; Wilkerson et al., 1989), and hence a maturity group zone (MG) designates each soybean cultivar to a defined area (Boerma and Specht, 2004). Due to these conditions, a common approach for implementing SS soybean in the Southern US is to move existing FS cultivars of later MGs from southern latitudes to northern latitudes. Previous research conducted in Southeastern US have confirmed that selection of cultivars in a FS cropping system is applicable to a SS cropping systems (Panter and Allen, 1989; Pfeiffer, 2000). In the Southern US, SS soybeans can take advantage of the long and mild fall season as later MG cultivars delay flowering and other critical reproductive stages (Hu and Wiatrak, 2012; Tutor, 2012). Moving later MGs from a southern to a northern location requires little to no additional resources and does not require a separate breeding program for SS soybean. Nevertheless, several studies that evaluated this approach have reported yield reduction for SS soybean. In the Mid-South region, SS soybean yield was reduced from 0.09 to 1.69% per day delayed after optimal planting date depending on the MG (Salmerón et al., 2016). Similarly, Egli and Cornelius (2009) reported that the rate of soybean yield decline was 1.1 % in the Upper South and 1.2% per day in the Deep South regions.

However, moving later maturing soybeans to a northern location for SS production is not practical for the Upper Midwest due to a much shortened growing season than the Southern US. In a SS system in the Upper Midwest, the growing season for soybean is limited from July to October, whereas FS soybean are planted in May and typically harvested in late September or early October (National Agricultural Statistics Service (NASS), 2010). The first fall killing frost arrives approximately four weeks to six weeks sooner in Minnesota than in Mid-Atlantic states

such as North Carolina and Virginia (Arguez et al., 2012). Delayed maturity due to late-planting for SS production can have negative consequences on soybean yield and seed quality if a killing fall frost occurs prior to complete crop maturation (Boersma, 2018). An approach for SS soybean production in the Upper Midwest is to move existing FS cultivars of earlier MGs from northern latitudes to southern latitudes. Such a strategy may be feasible for the Upper Midwest, though significant yield reductions are expected. Berti et al. (2015) showed yield reduced by 70% and 85% when using a soybean cultivar of MG 0.1 at Carrington, ND (47°48' N, 99°12' W) and at Prosper, ND (46°96'N, -97°01'W) respectively within a SS soybean system compared to using a MG 0.7 cultivar within a full-season production system. In the same study, a soybean cultivar of MG 00.1 was used in Morris, MN (45°59' N, 95°91' W) and yield was reduced by 60% for the SS soybean production system compared to a MG 1.3 cultivar planted for FS production conditions. Gesch et al. (2014) found that yield was reduced by 58% in Morris when a MG 00 soybean cultivar was planted in early July when compared to a cultivar of MG I planted in early May.

Indirect selections conducted in an existing FS soybean breeding program in northern latitude regions for the SS cropping system may be effective and would require little to no additional resources and efforts to develop a separate breeding program designated for SS soybean. Pfeiffer et al. (1995) found that indirect selection response of FS cultivars developed in a northern latitude state: Minnesota (latitude of 44°N) was predicted to be 0.94 as efficient when they were imposed within an early maturity soybean production system in a southern latitude state: Kentucky (latitudes of 37 to 38°N). However, to this point, very little to no research has been conducted to assess the implications of indirect selection in FS systems of a northern latitude region for SS soybean systems of a southern latitude region within the same state.

In addition to choices of MG to aid in cultivar selection, environmental effects can greatly affect yield variations within a SS planting system. Board and Hall (1984) reported that a combination of photoperiod and temperature is responsible for the early flowering and shorter vegetative growth phase of late-planted soybean in Southeastern US. Low radiation, a lack of soil moisture, daytime temperature below the optimal range of 24-34°C, and low nighttime temperature during late reproductive growth impact canopy photosynthesis, crop growth rate, and grain set for SS soybean production in Southern US (Bastidas et al., 2008; Egli and Bruening, 2000; Hansel et al., 2019; Kane et al., 1997a). In the Southeast US, adequate rainfall during the vegetative stage was found to be the most critical factor for soybean growth and development when planted in late June (Kane et al., 1997a). In the Upper Midwest, it was evident that the soil water availability in the months of June, July and August is critical for SS soybean to grow (Berti et al., 2015). In Carrington, ND, SS soybeans did not emerge following the harvest of winter camelina (*Camelina sativa* L.) because of limited rainfall prior to planting soybean in June, July, and August in 2013.

Crop phenology could greatly influence yield. Shortened vegetative stages (Board and Hall, 1984), seed-filling stage between R5-R7 (Ball et al., 2000; Calviño et al., 2003; Rowntree et al., 2014) and flowering to pod-setting stages from R1-R5 (Egli and Bruening, 2000) accounted for yield variation in SS soybean systems in the Southeast US, and the Pampas of Argentina (Calviño et al., 2003). Extended seed-filling duration (SFD) spanning from soybean growth stage R5 to R7 has been reported to improve yield within the FS system (Dunphy et al., 1979; Gay et al., 1980; Smith and Nelson, 1986), but little to no research has reported such findings for SS soybean. Planting date variations of FS production systems have been shown to

not affect SFD, but SS planting date may be too delayed and result in soil moisture and temperature stresses, both of which have been shown to affect SFD (Rowntree et al., 2014).

Although SS soybean double cropped with winter annuals has been investigated in the Upper Midwest, a lack of information is available about the variation in yield and seed quality among breeding lines within a SS system. Moreover, little is known about cultivar x cropping system interaction effects in the Upper Midwest. A diverse set of soybean varieties chosen from different companies and breeding lines could be examined to determine their suitability for double-crop soybean production (Boersma, 2018). A greater understanding of the genetic variation within a SS system and the interaction between cultivar and cropping system will assist breeding programs in designing strategies to enhance soybean yield and quality within double cropping systems, and whether cultivars developed in an existing FS-northern latitude breeding program could be directly used for SS soybean production in southern latitude regions. A study was carried out to better understand the effect of yield variation caused by different cultivars and their associated MGs within FS and SS production conditions in Minnesota. The objectives were to (i) evaluate variation in planting-date effects among breeding lines and cultivars, as well as any cultivar-by-system effects in southern latitude regions of Minnesota, (ii) determine if rank in performance in northern latitude regions of Minnesota can be used to help select cultivars for a SS system in southern latitudes of Minnesota, and (iii) evaluate aspects of phenology in relationship to yield within FS and SS conditions in southern latitude regions.

3.2 Material and methods

3.2.1 Site, Experiment, and Cultivars. Research was conducted in 2017 at Lamberton, MN and Waseca, MN, and in 2018 at Lamberton, Waseca, Westbrook, Crookston, and Shelly, MN (Table 3-1). Twenty-three soybean cultivars of MG 00 to 0 were selected for this study, and these

cultivars were bred and developed for the northern Minnesota FS growing environment. Cultivars used for the experiment originated from public and private breeding programs, with the public cultivars predominantly originating from the soybean breeding program at University of Minnesota. Site-specific information and soil characteristics for all the site-years are listed in Table 3-2. Crookston and Shelly were grouped into northern latitude regions ($> 47^{\circ}\text{N}$), and Lamberton, Waseca, and Westbrook were grouped into southern latitude regions ($< 45^{\circ}\text{N}$) (Figure 3-1).

All sites were fall-chiseled, and prepared in the spring with field cultivation. Sites were all rain fed environments, and soybean followed corn (*Zea mays* L.) harvested for grain. Plots were mechanically seeded in two rows, spaced 76 cm apart, at a rate of 370,650 seeds ha^{-1} in all site-years at southern-latitude regions, and four rows, spaced 25 cm apart at 400,000 seeds ha^{-1} at sites in northern-latitude regions. Planted plot dimensions at site-years in northern latitude regions were 2.4 m long and 2.0 m wide, and 2.4 m long and 1.5 m wide at site-years in southern latitude regions. Best management practices for commercial soybean production were used to establish, maintain, and harvest experimental plots. As necessary, weeds, diseases, and insects were controlled according to the recommended management guidelines for each site-year. Cultivars were seeded at two planting dates, with the FS planting date in mid-May in all the site-years, and the SS planting date around early July as desired target dates in southern latitude sites. The SS planting date was not imposed in northern-latitude regions due to infeasibilities of harvesting soybeans as late as late October in these regions. Weather observations, including daily minimum and maximum temperatures, and precipitation for all site-years, were obtained from the closest Global Historical Climatology Network Daily (GHCND) database provided by

the National Oceanic and Atmospheric Administration (NOAA) using the RNOAA package in R (Chamberlain, 2017).

The experimental design was a randomized complete block design with three replicates in a strip-plot arrangement for both cropping systems in southern-latitude regions. Planting date was the main treatment in each replication, and cultivars were the sub-treatment within each planting date. Regarding the FS cropping system in northern-latitude regions, a randomized complete block design with three replicates was planted.

3.2.2 Measurements. Soybean phenology was recorded twice weekly using the Fehr and Caviness (1977) scale throughout the growing season from emergence to maturity (VE to R8) in Waseca and Lamberton, MN. Number of days after planting were recorded at three-day intervals when 50% of the plants reached a given growth stage. The recording of vegetative growth stages terminated when a flower is detected on a soybean plant (R1). The duration of vegetative and reproductive growth periods were calculated based on the days plants spent between V1 and R1 and R1 to R7, respectively. Days to flowering (DTF) was measured as V to R1, and days to maturity (DTM) was measured between planting and physiological maturity. Flowering duration (FD), pod-development duration (PDD), and seed-fill duration (SFD) were determined based on the number of days between R1 and R3, R3 to R5, and R5 to R7, respectively (Bastidas et al., 2008; Rowntree et al., 2014).

Seed yield was measured by harvesting a 1.5 m by 2.4 m area within each plot from 18 October through 4 November in 2017 and 8 Oct. through 4 Nov. 2018. Yields were adjusted to 130g kg⁻¹ moisture, and reported in kilograms per hectare. Following harvest, approximately 500-g soybean subsamples were collected from each plot for seed protein and oil concentration analysis. Seed protein concentration and oil concentration were determined using a Perten DA

7200 Feed Analyzer (Perten Instruments, Stockholm, Sweden), and calibrations were provided by Perten Instruments.

3.2.3 Calculations and Data Analysis. Independent analyses were first conducted for yield, days to maturity, protein concentration, and oil concentration within both cropping systems in southern latitude regions, followed by a combined analysis of latitude-cropping system variations across FS-northern latitude and SS-southern latitude regions. Cultivars and cropping systems were considered fixed effects, and environments and replications nested in environment were considered random effects for the cropping system comparison in southern latitude regions. An analysis of variance (ANOVA) was conducted using the *aov* function of the R package *stats* (version 3.5.2; R Core Team, 2018), and treatments were considered significant at $\alpha = 0.05$. ANOVA was conducted for cropping system comparisons between FS and SS in southern latitude regions, and for the combined effect of latitude-cropping system between FS-northern and SS-southern latitude regions. Additionally, *lm* function was used to fit linear regression models for yield, days to maturity, protein concentration, and oil concentration across the two cropping systems in southern latitude regions, and for the FS cropping system in northern latitude regions. Least-square means of cultivars were obtained for each latitude-cropping system in both southern and northern latitude regions using the package *LSMEANS*. Spearman's rank correlation coefficients were generated to assess correlations among cultivar means within different cropping systems in southern latitude regions and for latitude-cropping system interactions using the *cor.test* function in R. Pearson correlation coefficients were calculated for different cropping systems across site-years for phenological variations to yield responses separately in southern latitude regions using the *cor.test* function in R.

3.3 Results and Discussion

3.3.1 Environment. Average temperatures were much higher in May 2018 at all the sites compared to the 2017 and the 30-yr average (Table 3-3). In June and July, similar air temperatures were observed in 2017 and 2018 across all the sites. Lower temperatures were found in August at Waseca and Lamberton in 2017 compared to the 30-yr average, and October had below-average temperatures at all the site-years in 2018. Cooler temperatures in August can cause negative effects to soybean seed-filling and other reproductive development towards physiological maturity, particularly for SS soybeans (Hansel et al., 2019; Seifert and Lobell, 2015). Freezing temperatures in October prior to soybean harvest can cause seed injury and reduce seed quality (Smith and Nelson, 1986). In the present study, fall killing frost did not arrive until the third week of October in 2017 at both locations in southern latitude regions, but it did occur sooner in 2018 across all latitudes. However, no damaged soybean seeds were observed in 2018 harvest. Drastically different precipitation occurred in 2017 and 2018 at Waseca and Lamberton. Except for June and September of 2017, precipitation at Lamberton and Waseca exceeded the 30-yr average in all other months. In 2018, precipitation was again much higher than the 30-yr average in Waseca and Lamberton throughout the growing season, except in July. In 2018 at Crookston, precipitation was well below the 30-yr average throughout the growing season, except in June. Optimal precipitation around seed development stages is critical to increase yield, particularly under rainfed growing conditions for SS production systems (Hu and Wiatrak, 2012).

3.3.2 Cropping System Effects on Seed Yield, Quality, and Maturity Date. Seed yield, protein and oil concentrations, and maturity date differed across different cropping systems and latitudes (Table 3-4). Average yield increased from low latitude region of SS (2141 kg ha⁻¹) to FS system (2854 kg ha⁻¹), and finally to the highest average yield (3266 kg ha⁻¹) observed in FS

system in northern latitude region. FS and SS-low latitude region had 13% and 34% of yield reduction, respectively compared to the FS system in northern latitude region. However, the range of seed yield varied drastically among cultivars within each cropping system. The lowest yield (1663 kg ha^{-1}) was found in the SS-low latitude region, and the highest yield (4069 kg ha^{-1}) was found in the FS-northern latitude region. The largest yield variation was found within the FS-southern latitude regions, and the least variation was found within the SS-southern latitude regions.

Protein and oil concentrations exhibited contrasting results between latitude and cropping system variations. Protein concentration was lowest in the FS-northern latitude (382 g kg^{-1}), intermediate in the FS-southern latitude (403 g kg^{-1}), and highest in the SS-southern latitude regions (409 g kg^{-1}). Oil concentration decreased from FS-northern latitude (199 g kg^{-1}) to FS-northern latitude (196 g kg^{-1}), and eventually to SS-southern latitude region (188 g kg^{-1}). The observed trend for protein and oil concentrations is consistent with previous research finding a contrasting relationship between protein and oil concentrations due to a delayed planting effect: protein concentration increases and oil concentration decreases (Helms et al., 1990; Kane et al., 1997b; Mourtzinis et al., 2017). Interestingly, the range of protein concentration among cultivars was the greatest (363 to 424 g kg^{-1}) in the FS-northern latitudes compared to all other cropping systems and latitude regions. The mean and distribution for oil concentration were more similar across all the cropping systems and latitude regions. Contrastingly, Assefa et al. (2019) found oil and protein both declined by delaying planting dates into late June at northern latitudes $40\text{--}45^{\circ}\text{N}$.

All the soybeans reached physiological maturity within a span of 10 days across all the cropping systems and latitude regions (Table 3-4). The average maturity date differed by roughly a month (30 days) between FS (9/9) and SS (10/5) cropping systems at southern latitude regions,

which is expected considering the MGs used in this study are generally too early for FS production systems in southern latitude regions. The earliest maturity date was detected in FS-southern latitude regions on 9/4, and the latest maturity date was found on 10/11 in SS-southern latitude regions.

3.3.3 Cropping System Effects in Southern Latitude Regions. All the treatment variables significantly impacted yield, protein, oil, and days to maturity for soybeans planted within FS and SS conditions in southern latitude regions (Table 5 and 6). Cropping system, environment, and the cropping system-by-environment interaction effects were significant for all the traits. Effects of cultivar, environment, and the interaction of cultivar-by-cropping system, cultivar-by-environment, and cultivar-by-cropping system-by-environment were significant ($p < 0.05$) for all traits of interest. Within the FS cropping conditions, only environment and cultivar impacted all the traits, and the interaction effect of cultivar-by-environment significantly impacted protein, oil, and days to maturity, but not yield. Similar significant effects were found within the SS cropping system in regards to environment, cultivar, and cultivar-by-environment for all traits considered.

Short-season soybeans produced on average 24.5% less yield than FS soybean system (Table 7). Cultivar MN0071 had the lowest yield in both FS and SS systems, and had the least difference for yield between the two cropping systems (-16.2%). The largest difference for yield (-33.6%) was found in cultivar MN0702CN, which had an above average yield (2937 kg ha^{-1}) within the FS system, and slightly below average yield within the SS system (2097 kg ha^{-1}). Interestingly, cultivar M09-240029 had the highest yield in both cropping systems, followed by cultivar 50-10. Cultivars PB-0146R2 and Sheyenne also produced above average yields across both cropping systems. These findings indicate that several cultivars had highly consistent yield

performances across the FS and SS cropping systems. However, the Spearman's rank correlation coefficient was low and not significantly different than zero, indicating an inability to predict SS cultivar yield from FS cultivar yield within the southern latitude region.

Protein and oil concentrations showed contrasting results between the two cropping systems. Two cultivars, M08-271313 and PB-0146R2 produced the most contrasting protein and oil concentrations, in which within the SS production system, protein concentration increased 7.8% and 5.8%, while oil decreased 9.4% and 6.6% in comparison to FS production system, respectively. Cultivar M07-303031 produced the highest protein concentration across both cropping systems (434 and 435 g kg⁻¹), and several other cultivars, including M10-207102, M11-238102, and MN0095 had above average and highly similar protein concentrations across both cropping systems. The highest oil concentration was obtained in cultivar 50-10 in both cropping systems (203 and 198 g kg⁻¹ respectively), followed by Henson, Lambert, M11-271062, and MN0304. Large differences for oil concentration between the two cropping systems were found in cultivars PB-0146R2 (-6.7%), M11-238102 (-6.9%), and M08-271313 (-9.4%). Spearman's correlation showed significant and high correlations for protein ($r^2=0.84$, $p<0.0001$) and oil concentrations ($r^2=0.89$, $p<0.0001$), which means there was little change in ranking for protein and oil concentration in southern-latitude regions between the two cropping systems.

Days to maturity was delayed on an average by 11.22% (11 days) from FS to SS production system. The largest range in days to maturity was observed in cultivars Lambert (94-109 days) between the two production systems. The earliest maturity within the FS system was found in cultivar 18X008N, MN0071, M10-207102, and M11-238102 (107 days), and the earliest maturity was observed in cultivar Lambert and Sheyenne (94 days) within the SS system. Cultivar Sheyenne had the earliest days to maturity within the SS system, and it had the second

earliest days to maturity in FS system. It was interesting to observe that soybeans planted within the FS system all matured from 107 to 109 days, and they had a longer variation that spanned from 94 to 102 days to maturity within the SS system. Much later MGs (1.2 to 2) of FS soybeans are generally planted in this latitude region, which can explain for the generalized compression for days to maturity observed within the FS system. Spearman's correlation for days to maturity was significant and quite high ($r^2 = 0.62$, $p < 0.0001$), which indicates results of this trait are highly consistent between FS and SS systems, and that the likelihood of cross-over interactions for days to maturity is very low.

Despite significant and highly correlated results found between FS and SS systems, conducting indirect selection within FS conditions using extremely early MGs may not be relevant for SS soybean productions. Full-season soybeans produced in southern-latitude regions of Minnesota typically use cultivars of relative maturity 1.5-2 (Lorenz et al., 2018), which will not mature prior to the fall killing frost if planted in a SS system. Rather, conducting indirect selection on earlier maturing cultivars developed in northern latitude regions may offer great importance for SS soybeans in southern latitude regions. Previous studies that investigated double cropping soybean within this latitude region in Minnesota have compared soybeans planted using one or two cultivars of the typical MGs (1 to 2) for FS production with one or two cultivars of soybeans in MGs (00 to 1) within a SS system (Gesch et al., 2014; Johnson et al., 2017). Therefore, a more comprehensive comparison between multiple cultivars of MG (1 to 2) that are typically used in FS production systems and cultivars of earlier MGs (00-1) will be needed to elucidate the variation for yield, seed quality, and days to maturity between FS and SS soybean production system in southern Minnesota. In southern Indiana, Boersma (2018) found that varieties of medium or full-season MGs provided the greatest opportunity to maximize grain

yield for double-crop soybean production, but full-season MGs may not be appropriate to use in high latitude regions such as in Minnesota, even in southern Minnesota. A latitude variation between southern Indiana (~38°N) and southern Minnesota (~44°N) can create huge differences for photoperiod and temperature effects within a SS soybean production. In another study conducted in Bornholm, Ontario, Canada (~43°N), the authors found that cultivars that were one relative MG earlier for FS production tended to yield better and had lower seed moisture conditions at harvest (Richter et al., 2013). The authors further recommended to consider using cultivars with one relative MG shorter than used for a normal planting date for SS soybean production, which by latitude considerations is highly similar to southern Minnesota.

3.3.4 Breeding Program Implications for Developing SS Soybean in Southern Latitude

Regions. Soybean yield is a highly complex trait (Setiyono et al., 2007; Xavier et al., 2018), and strong cultivar x environment (C x E) effects may exist between latitudes and environments that have contributed to the low correlation coefficient found for yield. In the present study, cultivar, latitude-cropping system, latitude-cropping system x environment, cultivar x latitude-cropping system, and cultivar x latitude-cropping system x environment effects were significant to all traits between northern latitude-FS system and southern latitude-SS system (Table 3-8). In particular, significant cultivar x cropping system x environment effects have led to the finding that proved C x E interactions exist between latitude-cropping system variations.

Furthermore, strong correlations detected between FS-northern and SS-southern latitude regions may suggest for non-crossover C x E interaction effects, and that indirect selection of early MG cultivars developed in FS-northern latitude regions will be applicable for SS production systems in southern latitude regions. Spearman's rank correlation between SS system and the FS-northern latitude regions showed a significant correlation for yield ($r^2 = 0.45$, $p < 0.03$), protein

concentration ($r^2 = 0.72$, $p < 0.001$), oil concentration ($r^2 = 0.65$, $p < 0.0001$), and days to maturity ($r^2 = 0.66$, $p < 0.001$). These results suggest that indirect selection may be feasible for all the traits characterized based on the significant correlations detected between FS-northern latitude region and SS-southern latitude region, though yield was the least significant trait.

3.3.5 Latitude-Cropping system Variations for Soybeans Planted within the FS system in Northern Latitude and the SS in Southern Latitude. Treatments of the study significantly impacted all the traits investigated for soybeans planted within the FS system in northern latitude regions (Table 3-8). Environment had significant impacts to yield, protein and oil concentrations, and days to maturity ($p < 0.05$) within the FS system in northern latitude regions. Cultivar was found significant to yield, protein and oil concentrations, and days to maturity. The cultivar by environment interaction effect only had significant effects to yield and days to maturity within the FS system in northern latitude regions. In comparison, all the treatments, include environment, cultivar, and the interaction effect of environment and cultivar had highly significant effects ($p < 0.0001$) to yield, protein and oil concentrations, and days to maturity within the SS system in southern latitude.

In northern-latitude regions, FS system produced on average 34.2% more yield than within SS system in southern-latitude regions (Table 3-10), with the smallest difference found in M08-434024 (23.9%), and the greatest difference in Sheyenne (46.8%). In addition, Sheyenne (4069 kg ha⁻¹) produced the highest yield, and MN0071 generated the lowest yield (1935 kg ha⁻¹) within the FS system in northern latitude regions. Interestingly, the two highest yielding cultivars found between the cropping system variation in southern latitude region: 50-10 and M09-240029 also produced well-above average yields within both FS and SS systems across the two latitude regions, generating 2543 and 2454 kg ha⁻¹ of yield, respectively. Furthermore, cultivars

18X008N, Integra 50069, and Sheyenne that had the largest difference in yield between FS and SS systems all observed above average yield in both cropping systems across the two latitude regions.

The general pattern for protein and oil concentrations was consistent with comparisons made between FS and SS cropping systems in southern latitude regions, though greater percentages of protein concentration increased and oil concentration decreased across different latitudes. It is noted that high temperatures experienced during R5 through R6 increases oil concentration and decreases protein concentration (Dornbos and Mullen, 1992). In addition, available soil moisture during R5 through R6 represents another important factor that may affect protein and oil content. As soil moisture declines during R5 through R6, previous research have found that protein concentration rises and oil concentration falls (Dornbos and Mullen, 1992; Foroud et al., 1993). These conditions could be more evident within a SS system, given the fact that SS soybeans are planted at a delayed planted date that may experience a lack of soil moisture and higher temperatures during R5 through R6. Year-to-year weather variations can influence temperatures that soybeans are exposed to and thus impact the protein and oil concentrations. Continued research that considers the effect of soil moisture conditions and temperature during R5-R6 will be needed to determine if these factors contribute to the variations observed in oil and protein concentrations within a SS system in southern Minnesota.

Protein concentration had much greater differences than oil concentration when comparing latitude-cropping system variations, which is in contrast to the differences detected for protein and oil concentrations between FS and SS cropping systems in southern latitude regions. Protein concentrations on average increased 7.4% and oil decreased 5.7% between FS-northern latitudes and SS-southern latitude regions, which are both higher than the variations

observed within the same latitude region. The largest difference for protein concentration was found in M07-303031 (14.2%). The highest protein concentration was found in M08-271313 (424 g kg⁻¹) within FS-northern latitude regions, followed by M11-238102 (404 g kg⁻¹) and PB-0146R2 (396 g kg⁻¹), and these cultivars also produced the highest protein concentrations within the SS system in southern latitude regions. The largest difference between FS-northern latitude regions and SS-southern latitude regions for oil concentrations was detected in M07-303031 (10.3%). The highest oil concentration was found in 50-10 (210 g kg⁻¹), which was the same cultivar that had the highest amount of oil concentrations within FS and SS systems in southern latitude regions. Above average oil concentrations for both FS and SS systems in northern and southern latitudes were also found in 18X008N (203 and 197 g kg⁻¹, respectively), Henson (209 and 196 g kg⁻¹, respectively), and MN0304 (206 and 194 g kg⁻¹, respectively).

Days to maturity delayed on an average by 16.6% (20 days) from FS to SS production system, and the largest delay was observed in cultivar M08-271313 (19.01%, 24 days). These findings confirm with results of another study conducted in Eastern Nebraska, in which a 40-day delay in planting caused maturity to delay by 25 days for 14 soybean cultivars of MG 3.0 to 3.9 (Bastidas et al., 2008). In the present study, days to maturity spanned from 112 days to 123 days, which is the longest of the three latitude-cropping systems. The earliest maturity occurred for cultivar Lambert (112 days), followed by cultivars 18X008N, Integra 50069, MN0095, and Sheyenne (all matured in 113 days) within the FS system in northern latitude regions. The cultivar that had the longest duration of days to maturity was M07-292111 (123 days). Overall, several cultivars had highly consistent days to maturity across the two latitude-cropping systems and matured much earlier than the average days to maturity, and they include Lambert, 18X008N, Integra 50069, and MN0095.

3.3.6 Variation of Growth-Stage Duration in Southern Latitude Regions. Measuring critical growth durations may help to elucidate the environmental effects on grain yield and determine their effects on yield in the evaluation of FS compared to SS soybean production systems in southern latitude regions. It was observed that soybeans planted within the SS system had on average 10 fewer days of vegetative stage than within FS cropping systems, and they had relatively similar days during flowering and pod setting periods (Table 3-11). Soybeans spent on average six fewer days in SFD within SS growing conditions, and overall 14 fewer days in DTM than planted within FS growing conditions. Pearson correlation coefficients between grain yield and the duration of different development stages are presented in Table 3-12. SFD, total reproductive stage, and DTM showed positive correlations to yield variation within the FS cropping system, though durations in vegetative, flowering, and pod setting stages had insignificant correlations to yield. The positive correlation found between longer SFD and high seed yield is consistent with previous research that reported similar findings in MG II and III cultivars planted under early May and early June planting dates (Boerma and Ashley, 1988; Gay et al., 1980; Rowntree et al., 2014). Soybeans planted within the SS system spent many fewer days in DTF, but they spent similar amount of days in other growth stages in comparison to soybeans grown within the FS system. No growth stage was found to be significantly correlated to yield within the SS system. Similarly, Kane et al. (1997) found that phenology durations measured for a planting date occurring in late-June in Kentucky did not have any strong relationship to yield variation for MG 00-IV cultivars, despite that earlier planting dates from late April to early June all observed significant correlations for durations of vegetative, pod-set, seed-fill, and total growth periods to yield. Continued evaluation of the effect of phenology to

yield will be needed to better understand the influence of phenology variations for SS soybean production systems in southern latitude regions.

3.4 Conclusions. This study establishes the first understanding of cultivar, environment, and C x E interaction effects for SS soybean in comparison to FS soybean productions systems within the same latitude region, and between two latitude regions in Minnesota. Results of the present study showed that latitude-cropping system variations had great influence on soybean yield, seed quality, and days to maturity. The lowest yield was found within the SS system in southern latitude regions and the highest yield was observed within the FS system in northern-latitude regions. SS soybeans in southern-latitude regions had higher protein but lower oil concentrations in comparison to FS soybeans in southern and northern latitude regions. Soybean cultivars of MGs 00-0 matured approximately 30 days later in SS-southern latitude regions when compared to the same cultivars grown in FS-northern latitude regions, and 20 days later than planted within FS-southern latitude regions. Significant C x E effects were found between FS-northern latitude and SS-southern latitude regions for yield, protein concentration, oil concentration, and days to maturity.

Indirect selection may be applicable to yield, protein and oil concentration, and days to maturity between the established breeding program for FS-northern latitude regions and the potential SS-southern latitude regions, though yield had the lowest correlation coefficient. These results indicate that crossover effects are unlikely to occur based on the positive and significant C x E effect detected for all traits investigated in the present study. Further investigations will be needed to better understand the C x E interaction effects found between northern latitude FS and southern latitude SS systems. Regarding critical growth stages, no specific growth stage was associated to yield within the SS cropping system and DTF was greatly compressed in

comparison to FS system in northern latitudes. Continued research investigating the effect of growth stages to yield will be needed to better characterize the important growth and development phases of SS soybean production systems in Minnesota.

Table 3-1. List of cultivars, source (NDSU: North Dakota State University, UMN: University of Minnesota), pedigree, and relative maturity group.

Cultivar	Source	Pedigree	Relative Maturity Group
18X008N	Private	N/A±	00.8
50-10	Private	N/A	0.1
Henson	Public: NDSU	ND03-5672 x Hamlin	0.0
Integra 50069	Private	N/A	0.05
Lambert	Public: UMN	M75-274 X M76-151	0.0
M07-254043	Public: UMN	UM3 X MN0606CN	0.0
M07-292111	Public: UMN	M01-315029 x MN1106CN	0.0
M07-303031	Public: UMN	MN1806SP X M99-340047	0.0
M08-271313	Public: UMN	M03-276016 x IA2064	0.1
M08-434024	Public: UMN	M02-333013 x M02-328023	0.0
M09-240029	Public: UMN	M03-163106 x OAC06-32	0.0
M10-207102	Public: UMN	M03-165068 x M04-419020	0.0
M11-238102	Public: UMN	LD05-16638 X PI603432B	0.0
M11-253-4066	Public: UMN	M03-149100 X MN0071	0.0
M11-271059	Public: UMN	MN0504 X MN0606CN	0.0
M11-271062	Public: UMN	MN0504 X MN0606CN	0.0
MN0071	Public: UMN	Harmony x OT92-8	00.7
MN0095	Public: UMN	M92-2700209 x M93-313135	00.9
MN0304	Public: UMN	Archer X Glacier	0.0
MN0702CN	Public: UMN	MN0902CN x ND01-3533	0.7
PB-0146R2	Private	N/A	0.2
SB88005	Private	N/A	00.5
Sheyenne	Public: UMN	Pioneer 9071 x A96-492041	0.08

±N/A, not available.

Table 3-2. Experimental details with respect to test sites, soils, and dates of planting and harvest at Lamberton, Waseca, Westbrook, Crookston, and Shelly, MN within full-season (FS) and double cropping (SS) production systems.

Latitude regions	Southern latitude (<45°N)					Northern latitude (>47°N)	
Location	Lamberton		Waseca		Westbrook	Crookston	Shelly
Latitude and Longitude	44°24' N, 95°32' W		44°07' N, 93°53' W		44°24' N, 95°31' W	47°82' N, 96°62' W	47°44' N, 96°80' W
Soil Series	Amiret loam		Webster clay loam		Normania loam	Colvin-Perella silty clay loams	Fargo silty clay
Soil family	Fine-loamy, mixed, superactive, mesic Calcic Hapludolls		Fine-loamy, mixed, superactive, mesic Typic Endoaquolls		Fine-loamy, mixed, superactive, mesic Calcic Hapludolls	Fine-silty, mixed, superactive, frigid Typic Calcicquolls	Fine, smectitic, frigid Typic Epiaquerts
Intended planting date	2017	2018	2017	2018	2018	2018	2018
	Actual planting date						
FS (May)	15 May.	16 May.	31 May.	17 May.	27 May.	23 May.	24 May.
SS (July)	27 June.	28 June.	6 July.	29 June.	29 June.	N/A±	N/A
Fall killing frost date	27 Oct.	12 Oct.	26 Oct.	11 Oct.	11 Oct.	11 Oct.	11 Oct.

±N/A, no double cropping planting treatment was imposed in northern latitude regions.

Table 3-3. Mean monthly air temperature and total monthly precipitation at Waseca, Lamberton, MN (southern latitude region) in 2017 and 2018 growing season and Crookston, MN (northern latitude region) during the 2018 growing season, and during the past 30 years.

Month	Waseca		Lamberton		Crookston
	2017	2018	2017	2018±	2018±
Air temperature (°C)					
May	14 (0) †	18 (4)	14 (-1)	18 (4)	17 (4)
June	21 (1)	21 (1)	21 (1)	22 (1)	21 (2)
July	23 (1)	21 (0)	22 (0)	22 (0)	21 (0)
August	19 (-2)	21 (0)	19 (-2)	21 (0)	20 (0)
September	17 (1)	18 (1)	18 (1)	18 (1)	14 (-1)
October	9 (1)	6 (-3)	9 (1)	6 (-3)	3 (7)
Precipitation (mm)					
May	129 (21)	134 (25)	152 (54)	115 (17)	49 (-24)
June	105 (-31)	147 (11)	69 (-48)	186 (70)	190 (84)
July	166 (43)	111 (-12)	102 (9)	157 (64)	37 (-37)
August	99 (-20)	122 (2)	125 (32)	92 (-1)	44 (-30)
September	51 (-49)	268 (167)	54 (-31)	167 (83)	67 (6)
October	105 (41)	80 (16)	150 (95)	71 (16)	93 (43)

± General weather conditions were found similar in Lamberton and Westbrook, and Shelly and Crookston due to proximity to a common weather station.

† Parenthetical values show departures from 30-yr averages at Waseca, Lamberton, and Crookston MN.

Table 3-4. Means and ranges of yield, protein, oil, and maturity date for cultivars in northern latitude regions: Crookston and Shelly, MN, and southern latitude regions: Waseca, Lamberton and Westbrook, MN within full-season (FS) and short-season (SS) cropping systems.

	Yield	Protein	Oil	Maturity date
	kg ha ⁻¹	g kg ⁻¹	g kg ⁻¹	Calendar date
FS System in Northern MN				
Mean	3266	382	199	9/18
Range	2763-4069	363-424	188-210	9/14-9/25
FS system in Southern MN				
Mean	2854	403	196	9/9
Range	1935-3476	388-434	185-203	9/4-9/14
SS system in Southern MN				
Mean	2141	409	188	10/5
Range	1663-2546	397-445	174-198	10/1-10/11

Table 3-5. Mean squares from analysis of variance of yield, protein, oil, and days to maturity for soybean cultivars planted in full-season and short-season latitude regions of southern Minnesota during 2017 and 2018.

Source \pm	Mean Square code	F-test statistic	Yield	Protein \ddagger	Oil \ddagger	Days to maturity
S	M1	M1/M3	18210.6***	68.1***	87.1***	121797***
E	M2	M2/M3	1491.7***	12.7***	40.0***	1828***
SE	M3	M3/M9	1045.2***	37.3***	4.6***	1700***
Replication/SE	M4	M4/M9	176.3***	1.3***	.50**	8
C	M5	M5/M7	462.7***	28.6***	6.9***	202***
CS	M6	M6/M8	160.5***	3.3***	.60***	27***
CE	M7	M7/M9	74.8***	5.5***	1.6***	33***
CSE	M8	M8/M9	49.7	0.7	.30	20***
Error	M9		39.7	1	.30	6

\pm S, cropping system; E, environment; C, cultivar.

\ddagger Data from Waseca cropping systems in 2018 were not obtained.

*Significant at the 0.05 probability level; ns, not significant.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

Table 3-6. Mean squares from analysis of variance of yield, protein, oil, and days to maturity for full-season (FS) and short-season (SS) systems at Waseca and Lamberton, MN in 2017 and 2018, and Westbrook, MN in 2018.

Source \pm	Mean square code	F-test statistic	Yield (kg ha ⁻¹)	Protein (g kg ⁻¹) \ddagger	Oil (g kg ⁻¹) \ddagger	Days to maturity (Day of the year)
FS						
E	M1	M1/M3	1939.83***	20.31***	21.93***	5330.4***
C	M2	M2/M3	492.83***	13.14***	2.85***	92.0
CE	M3	M3/M5	60.45	3.61***	1.14***	3.1
Rep/E	M4	M4/M5	170.86***	1.05*	0.32	7.1*
Error	M5		70.45	43.21	2.31	3.3
SS						
E	M1	M1/M3	602.60***	1.53	0.59	282.3***
C	M2	M2/M3	132.09***	31.33***	21.33***	70.36***
CE	M3	M3/M5	64.03***	18.58***	4.59***	16.61***
Rep/E	M4	M4/M5	181.87***	2.54**	0.73***	3.94
Error	M5		121.41	14.31	0.55	4.1

\pm E, environment; C, cultivar.

\ddagger Data from Waseca cropping systems in 2018 were not obtained.

*Significant at the 0.05 probability level; ns, not significant.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

Table 3-7. Averages, rankings (in parentheses), mean across all the cultivars, and Spearman's correlation coefficients for full-season (FS) and double cropping (SS) systems effect for yield, protein concentration, oil concentration, and days to maturity in southern latitude regions.

Cultivar	Yield (kg ha ⁻¹)			Protein (g kg ⁻¹)			Oil (g kg ⁻¹)			Days to maturity (Days after planting)		
	FS	SS	Difference in yield (%)	FS	SS	Difference in protein (%)	FS	SS	Difference in oil (%)	FS	SS	Difference in days to maturity (%)
18X008N	2875 (11)	2416 (4)	-16.4	390 (20)	398 (22)	1.8	201 (3)	197 (2)	-2	107 (1)	96 (6)	-11.46
50-10	3349 (2)	2543 (2)	-24.1	401 (12)	402 (16)	0.3	203 (1)	198 (1)	-2.5	108 (5)	97 (7)	-11.34
Henson	2493 (21)	2048 (17)	-17.9	404 (10)	403 (14)	-0.2	201 (3)	196 (3)	-2.5	108 (5)	97 (7)	-11.34
Integra 50069	2634 (18)	2193 (8)	-16.8	390 (22)	403 (14)	3.3	192 (19)	183 (18)	-4.7	108 (5)	95 (3)	-13.68
Lambert	3144 (6)	1795 (22)	-42.3	400 (13)	399 (19)	0.3	201 (3)	193 (5)	-4	109 (17)	94 (1)	-15.96
M07-254043	2595 (20)	1970 (20)	-24.5	410 (3)	407 (11)	-0.3	196 (13)	189 (11)	-3.6	108 (5)	102 (23)	-5.88
M07-292111	2968 (8)	2084 (14)	-29.8	407 (8)	412 (8)	1.2	197 (12)	188 (13)	-4.6	109 (17)	101 (22)	-7.92
M07-303031	2927 (10)	2122 (11)	-27.5	434 (1)	435 (2)	0.2	189 (20)	181 (21)	-4.2	109 (17)	97 (7)	-12.37
M08-271313	2682 (16)	2125 (10)	-21	410 (3)	445 (1)	7.8	192 (19)	174 (23)	-9.4	108 (5)	98 (15)	-10.20
M08-434024	3092 (7)	2454 (3)	-20.6	405 (9)	412 (8)	1.7	185 (23)	182 (19)	-1.6	109 (17)	99 (19)	-10.10
M09-240029	3476 (1)	2546 (1)	-26.8	404 (10)	410 (10)	1.5	196 (13)	192 (7)	-2	108 (5)	98 (15)	-10.20
M10-207102	2678 (17)	2015 (19)	-25	410 (3)	419 (5)	1.7	187 (22)	182 (19)	-2.7	107 (1)	98 (15)	-9.18
M11-238102	2751 (14)	2061 (15)	-25.4	410 (3)	428 (3)	3.9	189 (20)	176 (22)	-6.9	107 (1)	98 (15)	-9.18
M11-253-4066	2782 (13)	2214 (7)	-20.4	390 (20)	402 (16)	2.8	201 (3)	191 (9)	-5	109 (17)	97 (7)	-12.37
M11-271059	2604 (19)	2050 (16)	-21.3	391 (19)	399 (20)	2.1	199 (8)	193 (5)	-3	108 (5)	97 (7)	-11.34
M11-271062	2723 (15)	2048 (17)	-25.2	400 (13)	401 (18)	1	201 (3)	192 (7)	-4.4	108 (5)	97 (7)	-11.34
MN0071	1935 (23)	1663 (23)	-16.2	400 (13)	407 (11)	1.8	199 (8)	189 (11)	-5	107 (1)	97 (7)	-10.31
MN0095	2416 (22)	1839 (21)	-24.3	410 (3)	416 (6)	0.5	195 (15)	186 (16)	-4.6	108 (5)	95 (3)	-13.68
MN0304	2937 (9)	2349 (5)	-20.2	400 (13)	404 (13)	0.8	203 (1)	194 (4)	-4.4	108 (5)	95 (3)	-13.68
MN0702CN	3157 (5)	2097 (13)	-33.6	415 (2)	416 (6)	0.2	193 (17)	187 (15)	-3.1	109 (17)	99 (19)	-10.10
PB-0146R2	3329 (3)	2334 (6)	-29.9	397 (18)	420 (4)	5.8	198 (10)	185 (17)	-6.7	108 (5)	99 (19)	-9.09
SB88005	2840 (12)	2109 (12)	-25.8	388 (23)	397 (23)	2.3	198 (10)	191 (9)	-3.5	108 (5)	97 (7)	-11.34
Sheyenne	3260 (4)	2166 (9)	-34.5	400 (13)	399 (20)	0.5	195 (15)	188 (13)	-3.6	109 (17)	94 (1)	-15.96
LSD _(0.05)	87	68		6	6		4	5		2	3	
Mean	2854	2141	-24.6	403	410	1.8	196	188	-4.1	108	97	-11.22
Spearman's correlation	0.25 (p = 0.2508)			0.84 (p < 0.0001)			0.89 (p < 0.0001)			0.62 (p < 0.01)		

Table 3-8. Mean squares from analysis of variance of yield, protein, oil, and days to maturity for soybean cultivars planted in northern latitude-full-season and southern latitude-short-season

latitude regions during 2017 and 2018.

Source±	Mean Square code	F-test statistic	Yield	Protein‡	Oil‡	Days to maturity
Cropping system- latitude (CSL)	M1	M1/M2	23670.1 ***	607.8***	92.9***	32327***
CSL*Environment (E)	M2	M2/M7	474.9***	28.7***	14.6***	235***
Replication/CSLE	M3	M3/M7	345.8***	2.53***	0.9*	7
Cultivar (C)	M4	M4/M6	178.0***	28.2*	6.9***	108***
CCSL	M5	M5/M6	60.6***	2.9***	.50***	11**
CCSLE	M6	M6/M7	61.8***	1.9**	1.9**	17***
Error	M7		41.6	1.2	.35	5

‡ Data from Waseca cropping systems in 2018 were not obtained.

*Significant at the 0.05 probability level; ns, not significant.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

Table 3-9. Mean squares from analysis of variance of yield, protein, oil and days to maturity in response to cropping system-latitude (North-Full season and South-Short season) effects.

Source \pm	Mean square code	F-test statistic	Yield (kg ha ⁻¹)	Protein (g kg ⁻¹) \ddagger	Oil (g kg ⁻¹) \ddagger	Days to maturity (Days after planting)
North						
E	M1	M1/M3	19.10***	21.97***	0.32	45.92***
C	M2	M2/M3	104.85*	8.93***	1.79***	48.24***
CE	M3	M3/M5	892.92***	7.12**	1.54***	18.59***
Rep/E	M4	M4/M5	52.91**	1.53	0.46	2.19
Error	M5		72.1	4.23	7.66	2.45
SS						
E	M1	M1/M3	602.60***	1.53	0.59	282.3***
C	M2	M2/M3	132.09***	31.33***	21.33***	70.36***
CE	M3	M3/M5	64.03***	18.58***	4.59***	16.61***
Rep/E	M4	M4/M5	181.87***	2.54**	0.73***	3.94
Error	M5		100.32	10.43	15.42	3.3

\pm E, environment; C, cultivar.

\ddagger Data from Waseca cropping systems in 2018 were not obtained.

*Significant at the 0.05 probability level; ns, not significant.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

Table 3-10. Averages, yield rankings (in parentheses), mean across all the cultivars, and Spearman's rank correlation coefficients for northern-latitude (N) full-season and southern-latitude (S) short-season cropping systems effect for yield, protein, oil, and days to maturity.

Cultivar	Yield (kg ha ⁻¹)			Protein (g kg ⁻¹)			Oil (g kg ⁻¹)			Days to maturity (Day of the year)		
	N	S	Difference in yield (%)	N	S	Difference in protein (%)	N	S	Difference in oil (%)	N	S	Difference in days to maturity (%)
18X008N	3519 (4)	2416 (4)	-31.3	368 (20)	398 (22)	8.2	203 (5)	197 (2)	-3.0	113 (2)	96 (6)	-15.04
50-10	3951 (2)	2543 (2)	-35.6	373 (17)	402 (16)	7.8	210 (1)	198 (1)	-5.7	117 (12)	97 (7)	-17.09
Henson	3206 (12)	2048 (18)	-36.1	373 (17)	403 (14)	8.0	209 (2)	196 (3)	-6.2	117 (12)	97 (7)	-17.09
Integra 50069	3309 (8)	2193 (8)	-33.7	394 (5)	403 (14)	2.3	190 (21)	183 (18)	-3.7	113 (2)	95 (3)	-15.93
Lambert	3166 (15)	1795 (22)	-43.3	363 (23)	399 (21)	9.9	202 (6)	193 (5)	-4.5	112 (1)	94 (1)	-16.07
M07-254043	2807 (22)	1970 (20)	-29.8	378 (12)	407 (11)	7.7	196 (18)	189 (11)	-3.6	122 (20)	102 (23)	-16.39
M07-292111	3387 (5)	2084 (14)	-38.5	394 (6)	412 (8)	4.6	198 (15)	188 (13)	-5.1	123 (23)	101 (22)	-17.89
M07-303031	2890 (21)	2122 (11)	-26.6	381 (10)	435 (2)	14.2	202 (6)	181 (21)	-10.4	117 (12)	97 (7)	-17.09
M08-271313	3301 (9)	2125 (10)	-35.6	424 (1)	445 (1)	5.0	188 (22)	174 (23)	-7.4	121 (19)	98 (15)	-19.01
M08-434024	3225 (11)	2454 (3)	-23.9	383 (8)	412 (9)	7.6	196 (18)	182 (19)	-7.1	116 (11)	99 (19)	-14.66
M09-240029	3702 (3)	2546 (1)	-31.2	400 (3)	410 (10)	2.5	199 (12)	192 (7)	-3.5	120 (17)	98 (15)	-18.33
M10-207102	3313 (7)	2015 (19)	-39.2	380 (11)	419 (5)	10.3	197 (16)	182 (19)	-7.6	120 (17)	98 (15)	-18.33
M11-238102	3085 (19)	2061 (15)	-33.2	404 (2)	428 (3)	5.9	188 (22)	176 (22)	-6.4	115 (7)	98 (15)	-14.78
M11-253-4066	3108 (18)	2214 (7)	-28.8	377 (13)	402 (16)	6.6	197 (16)	191 (9)	-3.0	116 (11)	97 (7)	-16.38
M11-271059	3045 (20)	2050 (16)	-32.7	374 (15)	399 (19)	6.7	200 (10)	193 (5)	-3.5	115 (7)	97 (7)	-15.65
M11-271062	3354 (6)	2048 (17)	-38.9	366 (21)	401 (18)	9.6	207 (3)	192 (7)	-7.2	115 (7)	97 (7)	-15.65
MN0071	3110 (17)	1663 (23)	-46.5	374 (16)	407 (11)	8.8	196 (18)	189 (11)	-3.6	117 (12)	97 (7)	-17.09
MN0095	2763 (23)	1839 (21)	-33.4	393 (7)	416 (6)	5.9	202 (6)	186 (16)	-7.9	113 (2)	95 (3)	-15.93
MN0304	3184 (14)	2349 (5)	-26.2	376 (14)	404 (13)	7.4	206 (4)	194 (4)	-5.8	114 (6)	95 (3)	-16.67
MN0702CN	3147 (16)	2097 (13)	-33.4	383 (8)	416 (7)	8.6	202 (6)	187 (15)	-7.4	115 (7)	99 (19)	-13.91
PB-0146R2	3191 (13)	2334 (6)	-26.9	396 (4)	420 (4)	6.1	200 (10)	185 (17)	-7.5	122 (20)	99 (19)	-18.85
SB88005	3289 (10)	2109 (12)	-35.9	364 (22)	397 (23)	9.1	199 (12)	191 (9)	-4.0	117 (12)	97 (7)	-17.09
Sheyenne	4069 (1)	2166 (9)	-46.8	369 (19)	399 (20)	8.1	199 (12)	188 (13)	-5.5	113 (2)	94 (1)	-16.81
LSD (0.05)	103	79		5	7		3	3		2	2	
Mean	3266	2140	-34.2	382	410	7.4	199	1.8	-5.7	117	97	-16.6
Spearman's correlation	0.45 (p =0.03)			0.72 (p <0.001)			0.65 (p < 0.0001)			0.80 (p <0.001)		

Table 3-11. Means of days spent in growth stages include vegetative (V), flowering (R1-R3), pod setting (R3-R5), seed filling (R5-R7), complete reproductive phase (R1-R8), and days to maturity (DTM) of all cultivars at FS and SS planting dates (PD) during 2017 and 2018 at Waseca and Lamberton, MN.

Cropping system/PD	V	R1-R3	R3-R5	R5-R7	R1-R8	DTM
	<hr/> <i>Days</i> <hr/>					
FS (May PD)	42	12	12	38	71	112
Range	35-61	8-27	6-25	19-53	57-91	96-134
SS (July PD)	32	12	13	32	66	98
Range	28-38	6-23	5-21	15-49	56-80	89-110

Table 3-12. Correlations between yield, vegetative (V), flowering (R1-R3), pod setting (R3-R5), seed filling (R5-R7), complete reproductive phase (R1-R8), and days to maturity (DTM) at FS and SS planting dates (PD) during 2017 and 2018 at Waseca and Lamberton, MN.

Cropping system	V	R1-R3	R3-R5	R5-R7	R1-R8	DTM	Yield
FS PD							
V	1	0.08	0.47*	-0.44*	0.50**	0.02	0.03
R1-R3		1	0.02	0.21	0.58**	0.58**	0.36
R3-R5			1	-0.27	0.33	0.44*	0.26
R5-R7				1	0.63**	0.50*	0.66***
R1-R8					1	0.97***	0.77***
DTM						1	0.73***
Yield							1
SS PD							
V	1	.14	-.35	0.15	-0.11	0.46*	-0.03
R1-R3		1	-.23	-0.08	0.34	0.57**	0.14
R3-R5			1	-0.49*	0.28	-0.28	0.23
R5-R7				1	0.32	0.54**	0.33
R1-R8					1	0.58**	0.03
DTM						1	-0.22
Yield							1

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

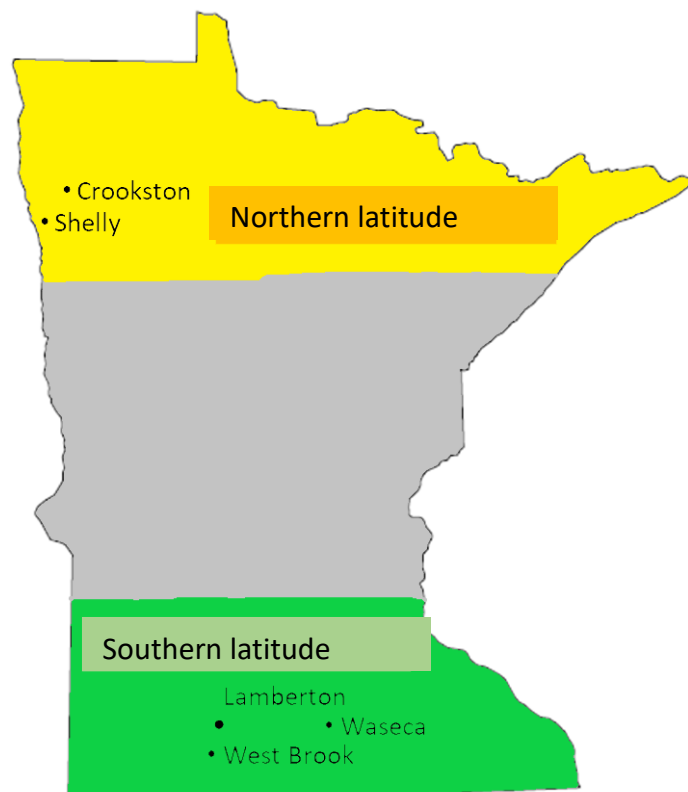


Figure 3-1. Map of all sites and latitude regions in Minnesota. Yellow area indicates the northern-latitude region, and green area indicates the low-latitude regions.

CHAPTER 4: STAKEHOLDER PRECEPTIONS TOWARDS DEVELOPING WINTER BARLEY AND THE WINTER BARLEY-SOYBEAN DOUBLE CROPPING SYSTEM IN MINNESOTA

4.1 Introduction. The development of modern and industrial agriculture has been characterized by great declines in biological diversity at the field and landscape levels (DeFries et al., 2004; Liebman and Schulte, 2015). This loss of biodiversity is particularly evident in the Upper Midwest, where cropping systems that once had small grains, hay, pasture and many other crops in addition to corn and soybean are now almost exclusively dominated by the latter two crops (Hooper et al., 2005; Hatfield et al., 2009). Increasing cropping diversity by reinvigorating the small grain production systems has shown to provide many potential ecological and economic benefits to farmers and the greater ecosystem. Hunt et al. (2019) identified that when comparing cropping systems of 2-year corn (*Zea mays*)–soybean (*Glycine max*) and more diversified cropping systems of 3-year corn–soybean–oat (*Avena sativa*)/clover (*Trifolium pratense*) and 4-year corn–soybean–oat/alfalfa (*Medicago sativa*)–alfalfa systems, N and P runoff losses were up to 39% and 30% lower, respectively, in the two more diversified systems than the 2-year corn–soybean monocropping system. Davis et al. (2012) found that diversifications of a corn–soybean cropping system through incorporating small grain crops can be a viable strategy for reducing dependency on synthetic fertilizers, pesticides, and fossil fuel inputs, while maintaining or even improving crop yields for the entire cropping system, farm income, pest suppression, and environmental quality.

In addition to potentially benefiting farmers and the environment, reinvigorating the production of small grains could benefit its potential end-users. From producing raw ingredients on-farm to the delivery of final processed products to the consumer, each step in any agri-food

production process is viewed as a critical link in its supply chain (Opara, 2003). Stakeholders are groups and individuals that could be influential or are influenced by an organization, or a supply chain (Parmar et al., 2010). In recent years, interests in local food systems has grown to a full-fledged popular social movement—the “locavore” movement in recent years (Werkheiser and Noll, 2014), and advocates for localism seek a short and transparent food supply chain. They do this for a variety of reasons, including: it uses fewer fossil fuel and carbon emissions; it is more socially and ecologically sustainable; it is more transparent and “traceable”; and most importantly, it can stimulate rural economic growth and development (Berman, 2011; Pimbert et al., 2015). This “locavore” movement may help to encourage for more locally-produced small grains.

Barley (*Hordeum vulgare*) is a key ingredient in brewing beer (Hertrich, 2013). A major link in a sustainable brewing supply chain is for brewers to source locally-grown and malted barley grains from farmers and maltsters (Hoalst-Pullen et al., 2014). Since 2011, the craft beer industry in Minnesota has experienced a greater than five-fold expansion. The Minnesota Brewery Pint Law, which was passed in the State Legislature in 2011, allows craft breweries to make and sell their wares on site (William, 2019). In 2012, 392,257 barrels of craft beer were sold in Minnesota, and 50 craft breweries were in operation. By 2018, over 696,000 barrels were sold and more than 175 craft breweries operated in Minnesota, which marks a 46% increase of craft beer sales from 2012 to 2018 (Brewers Association, 2019). The growing craft beer industry could stimulate interests for local barley production, and one potential crop that could be used in the local malting and brewing industries is winter barley. Important stakeholders involved in a winter malting barley supply chain may include farmers, maltsters, and brewers.

Winter barley has many potential advantages over traditional spring barley. Minnesota has had a long history of spring barley production, with peak production reaching 1.2 million acres in 1988, and a large portion of which was grown for malting end-use (Ash and Hoffman, 1989). However, spring barley acreage has since been declining, and this decline can be attributed to many complex reasons, particularly to a severe fungal disease called Fusarium Head Blight (FHB), (caused primarily by *Fusarium graminearum*), also known as “scab” (Windels, 2000; Paulitz and Steffenson, 2011). Winter barley typically heads early (early June) and may avoid weather conditions that are the most conducive to FHB infection and development. In addition, winter barley production can offer many potential environmental and economic opportunities to farmers, end-users, and many other stakeholders. When compared with winter wheat, winter barley utilizes lower N rate to achieve higher yields, which enables this crop to perform better in low-input conditions (Delogu et al., 1998). As a result, the reduced N requirement makes winter barley a better choice to reduce groundwater pollution due to nitrate leaching in winter and early spring. Winter barley that survives the winter may be double cropped with soybean, a dominating cash row crop that is currently grown over seven million acres of the cropping landscape in Minnesota (USDA-NASS, 2019). Soybean is not a known host of FHB. A double cropping system between winter barley and soybean could enable farmers to generate diversified income from two cash crops.

Interview and survey research methodologies are commonly used to assess attitudes (Fishbein and Ajzen, 2010; Heberlein, 2012) and the perception of risk (McGuire et al., 2013; Roesch-McNally et al., 2017; Basche and Roesch-McNally, 2017) that can influence stakeholders’ willingness to adopt new crops and end-uses. Semi-structured interviews are the most widely used forms of interviews in human and social sciences, and they feature in-depth

interviews where the respondents have to answer preset open-ended questions (Leavy 2014). Semi-structured interviews are based on semi-structured interview guides, which are schematic presentations of questions that need to be investigated by the interviewer (DiCicco-Bloom and Crabtree, 2006). Interview guides can provide researchers the opportunity to explore many respondents more systematically and to keep the interview focused (DiCicco-Bloom and Crabtree, 2006).

Previous survey and interview studies show that substantial numbers of farmers are interested in reconfiguring the landscape and cropping systems in ways that enhance resource conservation and biodiversity in the Upper Midwest. Nassauer (2009) examined the attitudes of Iowa farmers and farmland investors toward alternative land management systems, and fewer than 25% of the farmers and 10% of the investors ranked the conventional corn-soybean cropping systems as the most preferable. In Minnesota, survey responses from 1100 corn farmers indicated that farmers are more willing to plant cover crops than to replace current crops with perennial species (Levers et al., 2018). Across the greater US Corn Belt, both extensive survey and interview results show that farmers in more diversified watersheds, those who farm marginal land, and those who have livestock are more likely to use extended rotations (Roesch-McNally et al., 2018). However, very little research has examined stakeholder perceptions of a specific winter cash small grain crop that has the potential to diversify the current corn-soybean cropping systems in the Upper Midwest.

It is imperative to examine stakeholder perceptions towards winter barley as researchers are actively investigating for improved winter hardiness and malting quality for this crop. Patton (2016) conducted a study of surveying and interviewing brewers' perceptions on local malting barley in the East Tennessee and Southwest Virginia regions. The author concluded that there

was strong demand for sourcing locally grown malting barley among craft breweries in these regions. Currently, the on-going agronomic and breeding research for winter barley and a winter barley-soybean cropping system may supply farmers with necessary technical information and inputs in Minnesota. Nevertheless, the development of a new crop and the associated cropping system will require infrastructure and marketing development from agricultural stakeholders such as farmers, as well as key representatives from the supply chain and end-use markets. There remains a lack of understanding about the economic and environmental perceptions of a potential winter malting barley crop among local farmers and the malting end-users such as maltsters and brewers.

4.2 Research Purpose. Our goal is to increase the understanding of perceptions for a potential winter barley crop among stakeholders that include farmers, maltsters, and brewers in Minnesota. The objective of this interview project is to describe the views of local farmers, maltsters, and brewers about the development of winter barley in Minnesota. By first sharing the current status of winter barley breeding and agronomic management research with stakeholders, we then uncover the interests and concerns for winter barley and winter barley-soybean cropping system. Results of this study may point to opportunities to connect researchers and stakeholders to work collaboratively toward the adoption of winter barley on Minnesota cropping landscapes.

4.3 Research Methodology. The research model for this project is descriptive in nature and uses qualitative analysis. Individual interviews were conducted in a way that focused on the scope of environmental and economic sustainability towards the development of local winter barley grains in Minnesota. An advantage of individual interviews is that people are likely to speak more freely, without worrying what peers or other community members may think during group interviews (Salmen, 2000). In the present study, seventeen individual interviews were conducted

from May to June 2019 with seven farmers, seven brewers, and three maltsters in Minnesota (Table 4-1, 4-2, and 4-3). Each interviewee was encouraged to speak freely and bring to light issues of concern to the development of winter barley. These interviews all took place in the surroundings that make the interviewees feel the most comfortable, such as at their business or residence. Each interview lasted approximately one hour. Brewers were selected to represent a wide array of craft breweries from taproom to regional breweries that are primarily located in the Minneapolis-St. Paul (Twin Cities) area. According to the Brewers Association, craft brewery is defined as a brewery with an annual production under 6 million barrels, and are split into four types: regional brewery (production between 15,000 and 6,000,000 barrels); taproom brewery (sells 25 percent or more of its beer on-site and does not operate significant food services); brewpub (sells 25 percent or more of its beer on-site and operates significant food services); microbrewery (produces less than 15,000 barrels of beer per year and sells 75 percent or more of its beer off-site) (Brewers Association, 2018). Farmers were recruited via personal communications, at conferences and grower meetings. Seven farmers (two organic and five conventional) were eventually selected to participate in this project based on their previous small grain production experiences or their potential interests in growing small grains. Both craft (those that produce between 5 metric tons to 10,000 metric tons of malt per year) and conventional scale (produces larger than 400,000 metric tons of malt per year) maltsters in Minnesota were contacted and interviewed for the present project.

Each interview was recorded and transcribed verbatim. Different sets of questions were posed to three stakeholder groups (Appendix), and responses generated from each group were assessed separately. Throughout the interview, I emphasized that winter barley is currently under development, and is not in commercial production yet. Farmers were asked about their prior

production and marketing experience with small grain, followed by what characteristics it would need to have for them to be interested in planting it, and what benefits or challenges such a crop might provide. Maltsters were asked about their perceptions of winter malting barley and interests and concerns about the production and malting quality of winter barley. Brewers were asked about their use of local ingredients, interests and challenges with working with local ingredients, and their perceptions about winter barley, assuming that it could be sourced as an ingredient for beer brewing. Then a fact sheet about the current winter barley breeding and agronomy research program was shared with each interviewee. Afterwards, each interviewee was asked if he/she had any follow-up questions about winter barley, and if their perceptions have changed any about winter barley based on the information shared from the fact sheet. Finally, three diagrams of the nexus relationships between the three stakeholder groups were presented to each interviewee, and all the interviewees were asked about how they view about their relationship with each other within the interconnected links in the malting barley supply chain (Figure 4-1). Respondents were asked to choose a relationship diagram that he/she sees currently, and what they would like or expect to see in the future.

4.4 Results

4.4.1 Farmers. All the farmers interviewed said they would be interested in growing winter barley. As one said, *“If winter barley will survive in Minnesota, I will definitely grow it, and I’d like to see how it could do with double cropping soybeans”*. Interests in winter barley among farmers can be generally separated into two groups: i) conventional farmers considering a third crop to be incorporated in their current corn and soybean production systems, and ii) organic farmers who might incorporate winter barley along with other small grains into their current crop rotation plans as a cultural practice to suppress diseases and weeds.

A sustainable end-use market is the most important factor for conventional farmers to consider growing winter barley. All five conventional farmers shared that implementing a small grain crop such as winter barley would be of interest to them, because winter barley in rotation with corn and soybean could spread out machinery operations on a farm, particularly given the short planting and harvesting windows for corn and soybean. As one farmer said, *“Corn and soybean planting and harvesting window for me only lasts about 10 days during spring and the fall, so if I can grow something else that breaks this tight window, yeah, I’d be interested in growing winter barley”*. However, four out of the five conventional farmers expressed their concern for a lack of sustainable infrastructure that can support a local malting barley market due to a lack of small grain drying and storing facilities nearby and local grain elevators that would accept small grains. Two organic farmers responded that they could benefit from growing winter malting barley because there is already a viable market for organic barley seeds, and interests and demand for organic beer made of organic malting barley. *“Right now, yes, I can find a market for this organic barley, but I don’t grow a whole lot, because there is not so much demand for it...but I am very interested in winter barley, because if it can overwinter, then it can be more environmentally sustainable (than spring barley) and give me a cash crop by the summer.”* Potentially positive environmental implications associated with winter barley could draw a lot of attention among organic farmers.

All of the farmers who have attempted barley production said that the on-farm production management for malting barley is not too difficult, even for farmers who have no experience working with small grains. One farmer said that he would be able to control the grain protein content to meet malting quality standards by carefully applying nitrogen fertilizer. As one said, *“Equipment-wise the barley production only requires a grain drill during planting, otherwise the*

fungicide applications, weed control, and harvest equipment could all be shared with the corn and soybean production systems.” Another farmer noted that he did not experience major challenges with growing malting-grade barley, as long as barley is carefully rotated after soybean, not corn, and disease pressure such as FHB is controlled by carefully spraying fungicides. Nevertheless, three farmers pointed out that their concern for winter malting barley is that highly consistent grain quality still needs to be produced before the maltster and brewer would accept it, which is quite different from growing conventional corn and soybean. As one farmer discussed his experience with growing malting barley, *“This is definitely a crop that needs a lot of tender loving care, and we care very much about the genetics and breeding that are behind the development of a good variety.”*

Out of the seven farmers interviewed, three farmers indicated interests in attempting a winter barley-soybean double cropping system if both crops would be economically profitable crops. *“Since I am rotating it (spring barley) with soybean already, I don’t see any reason for why I wouldn’t grow soybean following the winter barley”*. In addition, many farmers were interested in learning more about the winter survival and double cropping system research, and collaborations with University of Minnesota (UMN) researchers to develop better winter hardy cultivars of winter barley. One farmer suggested that planting a mixture of winter barley and other possibly less winter-hardy crops such as oat could help the winter barley to better establish develop in the fall, and enhance its winter survival in the following spring. Two other farmers were curious about the tillage or stubble effects to enhance winter survival for winter barley. Both of them also shared their perspectives on no-till farming that they currently practice, which they believe will help increase the likelihood of winter survival. Overall, six farmers viewed that a winter survival rate of 75% and above would be satisfactory for them to consider growing this

crop, and three farmers asked for a more detailed enterprise budget sheet to understand the relationship between the rate of winter survival, yield, and potential profit margins. All of the farmers said that they are interested in learning more about the breeding progress towards more winter hardiness while maintaining malting characteristics for winter barley. They also indicated that they would like to be informed on breeding progress for this crop in the future.

4.4.2 Maltster. All three maltsters located in Minnesota were interested to find out more about the malting quality of winter barley, as high-quality winter barley may offer both economic and environmental benefits to the maltsters. The conventional maltster is interested in sourcing local winter barley because transportation costs and associated carbon footprint could be greatly reduced by working with a locally-produced crop. For the two craft maltsters, it is always a desirable business model to incorporate local barley into their malting operations, and in fact, both of the craft maltsters I interviewed are already using locally produced malting barley, and are very interested in winter barley and the potential winter barley-soybean double cropping system. One maltster said, *“(the double cropping system) May offer more interests to our farmers (suppliers) if they see that they could harvest both malting barley and soybean at the same year”*.

Two main concerns shared by maltsters were a stable supply of locally grown barley and a dearth of information about the malting quality of winter barley. If the local barley production continues to expand through the implementation of a potential winter barley crop, it may fit in the current malting operations of the conventional maltster, *“We are interested in working with Minnesota barley growers, but we depend more on growers in Western states because there are just more barley acreages, good yield, and good quality malting barley out there”*. Although there are only two craft maltsters currently operating in Minnesota, there is potential for

expansion of craft malting in the Upper Midwest. In 2018, two craft malt houses were launched separately in Iowa and Nebraska (Hammel, 2018; Purcell, 2018), and both businesses have the goal of supplying local barley to local craft breweries. Increased supply of winter malting barley and demand for more local malting barley from breweries and consumers could eventually foster the development of an economically and environmentally sustainable supply chain for the winter barley crop in Minnesota and surrounding regions.

In addition, all the maltsters shared interests and prospects on the potential malting quality of the winter barley crop. One maltster said that he believes both winter survival and malting quality must be enhanced through breeding advancements for this crop. Two maltsters said that they are optimistic about the breeding and agronomy research towards improving both winter survival and malting quality traits of winter barley, and they are interested in participating in collaborative projects with UMN researchers to test malting and brewing quality of potential winter barley experimental materials. All the maltsters expressed that they are very interested to see what the next phase of breeding advancement on winter barley will generate in relationship to malting and brewing quality understandings.

4.4.3 Brewer. Craft brewers focus on differentiation, and brewers have been releasing craft beer products for their unique tastes and likenesses. Many of the unique flavors come from the traditional slow brewing styles and recipes that have been perfected over the years (Kleban and Nickerson, 2011). A key ingredient that could impact the final flavor of beer is malt. Brewers always seek malt to contain five key characteristics: distinct flavors and aromas, low diastatic power, low total protein, lower Kolbach Index (ratio of Soluble Protein to Total Protein, or “S/T”), and low free amino nitrogen (FAN) (American Malting Barley Association, 2014). In addition, it was noted that craft brewers often have diverse flavor preferences for their beer

products, and the specific preference may be attributed with respect at a malting barley varietal level (Brewers Association, 2018). Assuming that a winter barley cultivar meets all the specifications, all the brewers interviewed said they would like to learn more and experiment whether a winter barley variety may offer a highly distinctive flavor profile and can be favored by their next product development needs and interests.

Brewers often incorporate locally-sourced niche ingredients such as fruits and other grain products in various brewing recipes. All the brewers interviewed in the present study said that they feature some types of local ingredients, whether it is honey (*Apis mellifera*), raspberry (*Rubus idaeus*), barley, wheat (*Triticum aestivum* L.), or intermediate wheatgrass-Kernza (*Thinopyrum intermedium*) in one or multiple beer products. Patton (2016) found similar interests among craft brewers in featuring local ingredients in the Mid-Atlantic region. The author further summarized that the general feelings among craft brewers is that not only does a brewer have to make a high quality beer, but a uniquely-flavored beer while using niche ingredients. Nevertheless, the incorporation of local ingredients must contribute to greatly enhance the taste quality of the beer, especially in the case of winter barley, *“I will be very curious about how this winter barley could be brewed, and what it will taste like, because it is such a key ingredient in beer making. At the same time, we must make sure that the consumers are satisfied and will want to return to these products, otherwise a beer won’t sell”*.

Overall, brewers were very curious about the impact of breeding and agronomy research to winter barley. It was evident that certain barley varieties have been acknowledged by some brewers to have notable flavor attributes (Herb et al., 2017), and these attributes have been sufficient to ensure the continued production of specific varieties even when newer varieties offer superior agronomic characteristics, malting performance, or both. Similar

acknowledgements have been observed in the present study. Three out of seven brewers mentioned that they are always looking for a new or exotic flavor in the final beer product. One brewer even said, *“I am really curious about winter barley...I wonder if one day, a variety bred in Minnesota could turn out to be the next Maris Otter, or even better the American version of Maris Otter, and this new variety could create so many potential possibilities for farmers, maltsters, and us”*. Maris Otter is an heirloom winter barley cultivar developed in the UK during the 1960s, and is still widely used by many brewers today. (Hertrich, 2013).

4.4.4 Stakeholder Engagement Assessment. A majority of interviewees across all the stakeholder groups selected the most interconnected nexus (a) as what they see for a prospective local winter barley supply chain (Figure 4-1). In comparison, 11 interviewees selected diagram (b) as what they see as the relationship for the three stakeholder groups now. The shift towards a more interconnected relationship between farmers, maltsters, and brewers suggests that more collaborations between the three stakeholder groups could be encouraged in determining the overall value of the winter barley crop throughout its supply chain and conducting research and extension to increase that value to the point that it is environmentally and economically sustainable. In addition, this stakeholder engagement question increased all stakeholders’ awareness about a potential winter barley supply chain for malting and brewing end-use, especially for the brewers. Three brewers actually shared with me that they are now more aware of a potential malting barley production market that involves local farmers, and if possible, they would like to source more locally grown barley, particularly winter barley if it becomes commercially available one day.

4.5 Conclusions and Future Prospective. We present the first stakeholder assessment using qualitative research methods to explore how three important groups of stakeholders of the

current malting barley supply chain (farmers, maltsters and brewers) perceive the potential of winter barley crop in Minnesota. Findings of this study will contribute to facilitate collaborations between important stakeholders and researchers towards further breeding and agronomic development and commercialization of winter barley. In addition, the study stimulated awareness for local malting barley, particularly the potential utilization of winter malting barley among brewers, who are the ultimate end-users of this crop.

All the interviewees agreed that winter barley would be a particularly attractive crop to grow or use for malting or brewing purposes. Six out of seven farmers said that a winter survival rate of 75% and above, and winter barley that exhibit high malting quality characteristics will be key considerations for them to value whether to plant this crop. Furthermore, farmers could generate income from two cash crops if double cropping soybean can follow winter barley production in the same year; maltsters could work with local supply chains to reduce logistic costs and carbon footprints; brewers may offer good quality and unique flavored beer to consumers. Continued improvement on winter survival and end-use malting and brewing quality for winter barley will be important to better determine its competitiveness, long-term sustainability, and end-use among other cash crops. In addition, proactive public policy programs and government incentives may contribute to strengthen the development of local winter barley production and end-use in Minnesota. For example, in New York, a Farm Brewery License Program was established in 2016 with the goal to incentivize farm breweries to source 20% of their ingredients locally when making malted beverages, and this percentage will increase to 90% by 2024 (Hmielowski, 2017; Stempel, 2016). Dedicated local food programs, sustained research, and sound policy will all be needed to facilitate a sustainable transition to a more diverse agroecosystem in Minnesota.

Table 4-1. Description of farmers interviewed.

	Years farming	Cash Crops grown	Small grain production over the last five years?	Livestock	Area (Acres)	Farm type
Farmer 1	15	Corn, soybean	Yes, last 4 years	Cattles	2000	Conventional
Farmer 2	31	Corn, soybean	Yes, last 2 years	Hogs, goat	400	Conventional
Farmer 3	47	Corn, soybean, wheat, barley, oat	Yes, >5 years	Cattles	400	Organic
Farmer 4	45, shifted to organic in 2001	Corn, soybean, wheat, barley, oat	Yes, >5 years	Chicken	1200	Organic
Farmer 5	30	Corn, soybean	No	N/A	400	Conventional
Farmer 6	26	Corn, soybean, rye, wheat, barley	Yes	N/A	1000	Conventional
Farmer 7	29	Corn, soybean, alfalfa	No	Cattle	1000	Conventional/ Organic (some transitioned, and some have not)

Table 4-2. Description of brewers interviewed.

	Brewery type¶	Local ingredients used in one or more beer products	Years in business
Brewer 1	Regional	Barley	>30
Brewer 2	Regional	Barley	>30
Brewer 3	Taproom brewery	Wild rice, Kernza*	2
Brewer 4	Brewpubs	Honey, rhubarb, wild rice	5
Brewer 5	Taproom brewery	Kernza	6
Brewer 6	Microbrewery	raspberry, rye, wheat	4
Brewer 7	Brewpubs	Barley, honey, raspberry	4

¶Regional brewery: A brewery with an annual beer production of between 15,000 and 6,000,000 barrels; Taproom brewery: A professional brewery that sells 25 percent or more of its beer on-site and does not operate significant food services; Brewpub: A restaurant-brewery that sells 25 percent or more of its beer on-site and operates significant food services; Microbrewery: A brewery that produces less than 15,000 barrels of beer per year and sells 75 percent or more of its beer off-site (Brewers Association, 2018).

Table 4-3. Description of maltsters interviewed

	Type of malting facility¶	Using traceable local barley	Serving regions
Maltster 1	Craft	Yes, 100% local from Minnesota	Urban and rural areas throughout MN and ND
Maltster 2	Craft	Yes, some from Minnesota, and some from North Dakota	Urban and rural areas throughout MN and ND
Maltster 3	Conventional	No	Nationally

¶ Craft: produces between 5 to 10,000 metric tons of malt per year. Conventional: produces greater than 400,000 metric tons of malt per year (Natalie Daher, 2016; Craft Maltsters Guild, 2018).

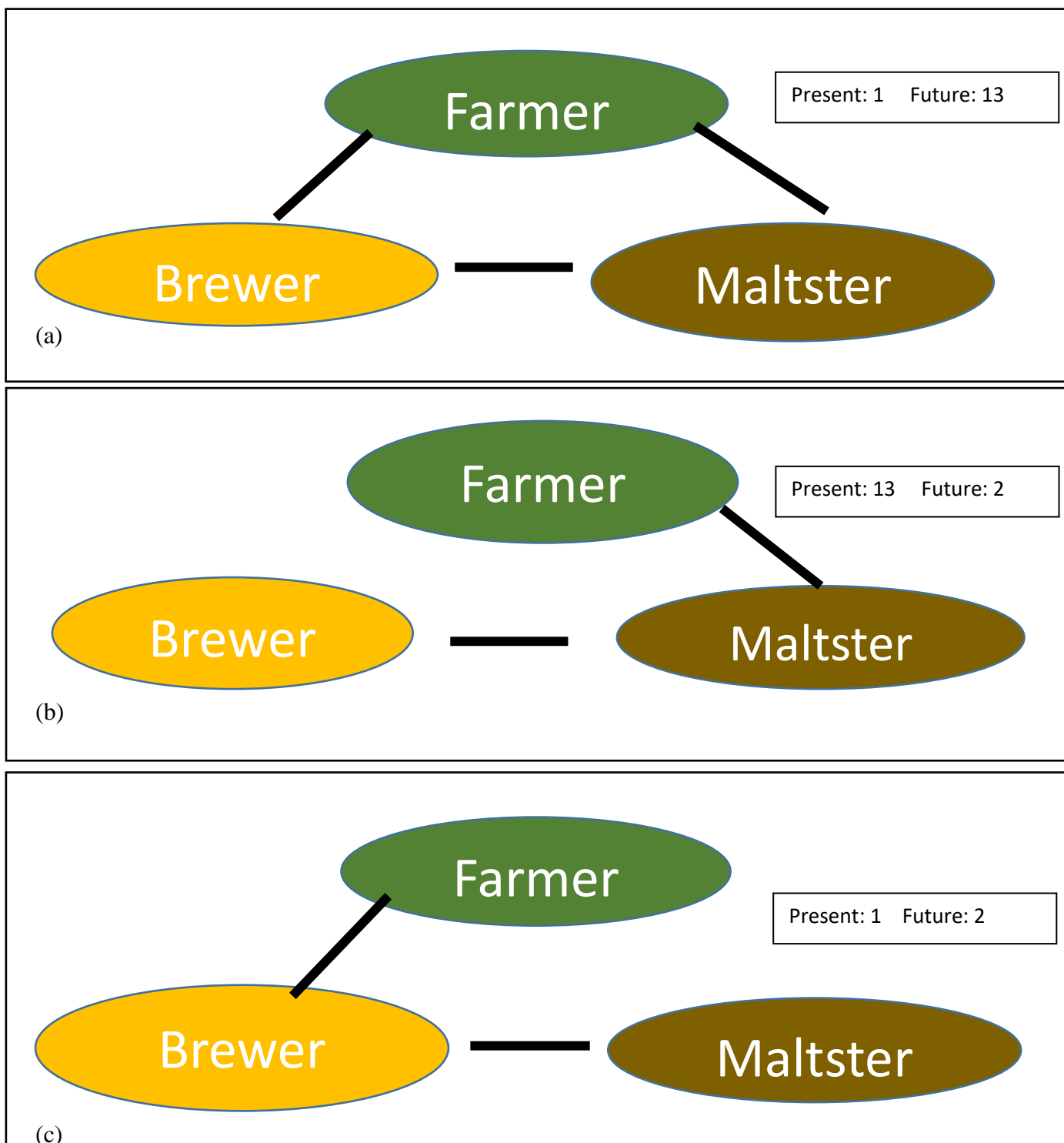


Figure 4-1. Interviewees were asked to select one of the nexus diagrams (a, b, or c) that represent the relationships between three key stakeholder groups: farmer, brewer, and maltster they view today and what they envision for the future of winter and local malting barley supply chain development.

APPENDIX. INTERVIEW GUIDE

Interview plan

1. Introduce myself and the interview project
2. Ask some background questions, separated for each stakeholder group
3. Present the factsheet
4. Follow up with winter barley-specific questions, separated for each stakeholder group

Self-introduction and background about the interview project

Thank you for taking the time to meet with me today. I have several questions for you about the potential production and end-use of the winter barley crop.

I am currently a Master student advised by Dr. Kevin Smith in the barley breeding research program in the Department of Agronomy and Plant Genetics at the University of Minnesota. This interview is part of my Master's thesis project.

The goal of this project is to understand the potential market interest for winter barley and facilitate collaborations and opportunities between researchers and potential stakeholders of the winter barley crop in Minnesota and surrounding regions. If at any point you would like to skip a question or end the interview, please feel free to do so. You are under no obligation to participate and choosing not to participate will not affect your relationship to the University of Minnesota in any way.

Our interview will be carried out with a few general background questions about your business operations, then I will present a fact sheet about the current status of winter barley development, local barley production, and malting operations in Minnesota. Following that, I will ask you a few more questions based on the information presented on the fact sheet. Do you have any questions for me before we get started?

Background questions

Farmers:

- Tell me about your farm enterprise and how you are currently operating. What type of operation do you run on your farm currently? (crops, livestock, or both?) What types of crops/animals do you have? Are you an organic or conventional farmer?
- Have you had any small grains on your farm before (Or any farm history of producing small grains that you can remember)?
 - If answer is yes: please describe your experience with small grains. What equipment and crop management strategies do you use in small grain productions? Please describe your marketing and distribution experience with small grains?
- Do you currently grow any cover crops on your farm? If you do, what do you currently grow?

Maltsters:

- Please describe your business's malting operation as far as its capacity, scale, clientiles, future plans, and others?
- If you don't mind me asking, where do you source your malting barley? Please explain the percentage of what your current local sourcing is and an approximate estimate of miles between your business and your source(s)?
- Do you source or work with any local organic grain farmers? Do you have any interest to explore in this area?
- How important are locally produced ingredients to your business? Please explain how sourcing local barley have or would affect the following variables:
 - Logistics
 - Pricing
 - Marketing
 - Quality
 - Consistency
 - Reliability
 - Others?

Brewers:

- Tell me about the history of your business. Please describe your business's brewing operation as far as its capacity, scale, distribution, clientiles, future plans, and others?
- How do you market and promote your beverage products that contain malt barley?
- Do you have any organic product or are you interested in making products out of organic ingredients? Or would you prefer local ingredients? Or both organic and local?
- Do you use any locally produced malt in your beverage products?
 - Yes: Where do you source your malt? How long have you sourced local malt? If you have product(s) made with local barley already, have you observed any changes in (examples: increase/decrease sales, marketing, quality, and others) to your business?

Fact sheet about winter barley

Breeding and agronomics:

- Minnesota has a long history of spring barley production, and the barley research program dates back to 1900 at the University of Minnesota. Currently, 70% of spring barley is produced in the Northwestern region (Marshall County) in Minnesota.
- A new research interest to develop winter barley suitable for Minnesota and surrounding Upper Midwest regions is currently underway.
- As a cover crop, winter barley has the potential to
 - Provide continuous-living cover on the cropping landscape
 - Scavenge recessive nitrate remaining in soil and water sources
 - Lower disease pressure for scab
 - Minimum management necessary
 - Rotation crop
- Currently, researchers are developing more winter hardy winter barley that can survive the winter and be harvested as grains for potential malting end-use
- Winter barley has shown to out-yield spring barley and produce high-quality malt in several states, include Oregon, Michigan, and Idaho.
- Six out of ten trials of winter barley survived winters in 2010-2019 in Central to Southwestern MN.
- Preliminary research has found that winter barley that had 70-88% of winter survival producing the highest amount of yield.

Marketing and existing end-use infrastructure:

- Minnesota is home to the world's largest malt house, Rahr Malting Co. (Shakopee, MN). Over 25% of all American-brewed beers contain Rahr malt, and in Minnesota it's over 90%. Rahr produces 70,000 metric tons to a total of 460,000 metric tons of malt annually. That's enough malt to brew 6 billion bottles of American craft beer each year.
- In addition to Rahr, Anheuser-Busch has a malt plant in MN (producing about 8 million bushels, or 130,000 metric tons of pale malt each year), along with several other independent maltsters, include Vertical Malt (Crookston), Maltwerks (Detroit Lakes), and Able Seedhouse and Brewery (Minneapolis).
- More than 178 breweries have been established in Minnesota as of 2018, and this number continues to grow. Over 644,000 barrels of craft beer are produced in Minnesota in 2018, which ranks the state #12 for craft beer production in the country.

Follow-up questions:

Grower:

- What are additional questions do you have about this new crop?
- Based on the fact sheet presented above, would you have an interest to plant winter barley as a cover crop? Does any information presented on the fact sheet attract you?
- Regardless if you answered no to the initial question about experience working with small grains, do you have any experience working to incorporate small grains into your crop rotation programs? If you do, please describe.
- Please take a look at the three diagrams attached, which diagram do you see currently in your business when you interact with partners such as maltsters and brewers? What would you like to see?
- What are your concerns about winter barley and/or any information based on the fact sheet?

Maltster:

- What additional questions do you have about winter barley?
- Based on the fact sheet presented above, would you be interested to contract winter barley at some point in the future? Why or why not?
- Given the information we have presented to you, (considering that many businesses have adopted environmental stewardship and sustainability programs), what do you find attractive in winter barley that fits in your business? How do you envision contracting winter barley?
- Please take a look at the three diagrams attached, which diagram do you see currently in your business when you interact with partners such as farmers and brewers? What would you like to see?
- What challenges and concerns have you experienced, or do you foresee when sourcing local barley (spring)?

Brewer:

- What additional questions do you have about winter barley?
- Based on the fact sheet presented above, do you find winter barley attractive as a potential raw ingredient in your products?
- Please take a look at the three diagrams attached, which diagram do you see currently in your business when you interact with partners such as farmers and maltsters? What would you like to see?
- Would you share your experience marketing locally grown raw ingredients in your products? How would you communicate with your customers about winter barley? How valuable is winter barleys ecosystems services to your business model?

- What challenges and concerns do you have or do you foresee for sourcing local barley?

BIBLIOGRAPHY

Aase, J.K., and F.H. Siddoway. 1979. Crown-depth soil temperatures and winter protection for winter wheat survival. *Soil Sci. Soc. Am. J.* 43: 1229-1233.

doi:10.2136/sssaj1979.03615995004300060036x.

- Adebiyi, J., Schmitt Olabisi, L., Snapp, S., 2016. Understanding perennial wheat adoption as a transformative technology: evidence from the literature and farmers. *Renew. Agric. Food Syst.* 31, 101–110. doi:10.1017/S1742170515000150
- Ash, M., and L. Hoffman. 1989. Barley Background for 1990 Farm Legislation. USDA-Economic Research Service. Washington, DC.
- Alley, M., Roygard, J.K.F., 2002. Intensifying agronomic crop production systems. Virginia Polytechnic Institute and State University, Blacksburg, VA.
- American Malting Barley Association, 2014. Ideal Commercial Malt Criteria. Madison, WI.
- Andrews, C.J., 1996. How Do Plants Survive Ice ? *Ann. Bot.* 78, 529–536.
- Andrews, C.J., M.K. Pomeroy, W.L. Seaman, G. Butler, P.C. Bonn, and G. Hoekstra. 1997. Relationships between planting date, winter survival and stress tolerances of soft white winter wheat in eastern Ontario. *Can. J. Plant Sci* 77:507–513.
- Andrews, C.J., Pomeroy, M.K., 1977. Changes in Survival Of Winter Cereals Due To Ice Cover And Other Simulated Winter Conditions. *Can. J. Plant Sci.* 57, 1141–1149. doi:10.4141/cjps77-169
- Andrews, C.J., Pomeroy, M.K., 1981. The effect of flooding pretreatment on cold hardiness and survival of winter cereals in ice encasement. *Can. J. Plant Sc.* 61, 507–513.
- Arslan, M., Isler, N., Caliskan, S., 2006. Effects of cultivar maturity on growth and yield of double cropped soybean. *Acta Agric. Scand. Sect. B - Plant Soil Sci.* 56, 39–46. doi:10.1080/09064710510029060
- Arguez, A., Durre, I., Applequist, S., Vose, R.S., Squires, M.F., Yin, X., Heim, R.R., Owen, T.W., Arguez, A., Durre, I., Applequist, S., Vose, R.S., Squires, M.F., Yin, X., Jr., R.R.H., Owen, T.W., 2012. NOAA's 1981–2010 U.S. Climate Normals: An Overview. *Bull. Am. Meteorol. Soc.* 93, 1687–1697. doi:10.1175/BAMS-D-11-00197.1
- Ash, M., Hoffman, L., 1989. Barley Background for 1990 Farm Legislation. Washington, DC.
- Assefa, Y., L.C. Purcell, M. Salmeron, S. Naeve, S.N. Casteel, P. Kovács, S. Archontoulis, M. Licht, F. Below, L. E. Lindsey, J. Gaska, S. Conley, C. Shapiro, J. M. Orłowski, B. R. Golden, G. Kaur, M. Singh, K. Thelen, R. Laurenz, D. Davidson, I.A, Ciampitti. 2019. Assessing variation in us soybean seed composition (protein and oil). *Front. Plant Sci.* 10: 298. doi: 10.3389/FPLS.2019.00298.
- Badr, A., M, K., Sch, R., Rabey, H. El, Effgen, S., Ibrahim, H.H., Pozzi, C., Rohde, W., Salamini, F., 2000. On the origin and domestication history of barley (*Hordeum vulgare*). *Mol. Biol. Evol.* 17, 499–510. doi:10.1093/oxfordjournals.molbev.a026330
- Ball, R.A., Purcell, L.C., Vories, E.D., 2000. Short-season soybean yield compensation in response to population and water regime. *Crop Sci.* 40, 1070–1078. doi:10.2135/cropsci2000.4041070x
- Bandillo, N.B., Anderson, J.E., Kantar, M.B., Stupar, R.M., Specht, J.E., Graef, G.L., Lorenz,

- A.J., 2017. Dissecting the genetic basis of local adaptation in soybean. *Sci. Rep.* 7. doi:10.1038/s41598-017-17342-w
- Basche, A.D., and G.E. Roesch-McNally. 2017. Research topics to scale up cover crop use: Reflections from innovative Iowa farmers. *J. Soil Water Conserv.* 72(3): 59A-63A. doi: 10.2489/jswc.72.3.59A.
- Bastidas, A.M., Setiyono, T.D., Dobermann, A., Cassman, K.G., Elmore, R.W., Graef, G.L., Specht, J.E., 2008. Soybean sowing date: The vegetative, reproductive, and agronomic impacts. *Crop Sci.* 48, 727–740. doi:10.2135/cropsci2006.05.0292
- Batal, A., Dale, N., 2016. Ingredient analysis table: 2009 edition. *Feedstuffs*, Sept. 10 2009.
- Bauer, A., A.B. Frank, and A.L. Black. 1993. A crop calendar for spring wheat and for spring barley. *N. D. Farm Res.* 49:21–25.
- Bergjord Olsen, A.K., T. Persson, A. de Wit, L. Nkurunziza, E. Sindhøj, and H. Eckersten. 2018. Estimating winter survival of winter wheat by simulations of plant frost tolerance. *J. Agron. Crop Sci.* 204: 62–73. doi: 10.1111/jac.12238.
- Berman, E. 2011. Creating a Community Food System: The Intervale Center. *J. Agric. Food Inf.* 12(1): 3–11. doi: 10.1080/10496505.2011.539527.
- Berti, M., Gesch, R., Johnson, B., Ji, Y., Seames, W., Aponte, A., 2015. Double- and relay-cropping of energy crops in the northern Great Plains, USA. *Ind. Crops Prod.* 75, 26–34. doi:10.1016/j.indcrop.2015.05.012
- Berti, M., Johnson, B., Ripplinger, D., Gesch, R., Aponte, A., 2017. Environmental impact assessment of double- and relay-cropping with winter camelina in the Northern Great Plains, USA. *Agric. Syst.* 156, 1–12. doi:10.1016/J.AGSY.2017.05.012
- Berti, M., Johnson, B., Ripplinger, D., Gesch, R., Aponte, A., 2017. Environmental impact assessment of double- and relay-cropping with winter camelina in the northern Great Plains, USA. *Agric. Syst.* 156, 1–12. doi:10.1016/J.AGSY.2017.05.012
- Berti, M., R. Gesch, B. Johnson, Y. Ji, W. Seames, A. Alfredo. 2015. Double- and relay-cropping of energy crops in the Northern Great Plains, USA. *Ind. Crops Prod.* 75: 26–34. doi: 10.1016/j.indcrop.2015.05.012.
- Board, J.E., Hall, W., 1984. Premature flowering in soybean yield reductions at nonoptimal planting dates as influenced by temperature and photoperiod. *Agron. J.* 76, 700–704.
- Boerma, H.R., Ashley, D.A., 1988. Canopy photosynthesis and seed-fill duration in recently developed soybean cultivars and selected plant introductions. *Crop Sci.* 28, 137-142. doi:10.2135/cropsci1988.0011183X002800010029x
- Boerma, H.R., Specht, J.E., 2004. Soybeans: Improvement, Production, and Uses, 3rd Edition. ed. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, WI. doi:10.2134/agronmonogr16.3ed.frontmatter
- Boerma, H.R., Specht, J.E., Heatherly, L.G., Elmore, R.W., 2004. Managing Inputs for Peak Production, in: Soybeans: Improvement, Production, and Uses. American Society of

- Agronomy, Crop Science Society of America, and Soil Science Society of America, pp. 451–536. doi:10.2134/agronmonogr16.3ed.c10
- Boersma, S.J., 2018. Double-crop soybean response to maturity group and plant population in the Ohio River Valley Region. Purdue University, West Lafayette, IN.
- Borchers, A., Truex-powell, E., Nickerson, C., Wallander, S., 2014. Multi-cropping practices : recent trends in double cropping. Economic Information Bulletin Number 125. Economic Research Service. USDA. Washington, DC.
- Brakke, J.P., Francis, C.A., Nelson, L.A., Gardner, C.O., 1983. Genotype by Cropping System Interactions in Maize Grown in a Short Season Environment. *Crop Sci.* 23, 868-871. doi:10.2135/cropsci1983.0011183X002300050012x
- Brewers Association, 2018. National Beer Sales & Production Data. URL <https://www.brewersassociation.org/statistics/number-of-breweries/> (accessed 6.18.19).
- Brewers Association. 2018. Craft Brewer Defined. <https://www.brewersassociation.org/statistics/craft-brewer-defined/> (accessed 18 June 2019).
- Brouwer, B.O., P.B. Schwarz, J.M. Barr, P.M. Hayes, K.M. Murphy, and S.S. Jones. 2016. Evaluating barley for the emerging craft malting industry in western Washington. *Agron. J.* 108:939–949. doi:10.2134/agronj2015.0385.
- Browning, P.W., Holshouser, D.L., Thomason, W.E., Gordon, C.-C., Groover, E., Balota, M., 2011. Agronomic and economic comparison of full-season and double-cropped small grain and soybean systems in the Mid-Atlantic USA. Virginia Polytechnic Institute and State University, Blackburg, VA.
- Brummer, E.C., Barber, W.T., Collier, S.M., Cox, T.S., Johnson, R., Murray, S.C., Olsen, R.T., Pratt, R.C., Thro, A.M., 2011. Plant breeding for harmony between agriculture and the environment. *Front. Ecol. Environ.* 9, 561–568. doi:10.1890/100225
- Bundy, L., Andraski, T., Wolkowski, R., 1993. Nitrogen credits in soybean corn crop sequences on 3 soils. *Agron. J.* 85, 1061–1067. doi:10.2134/agronj1993.00021962008500050020x
- Burrows, M. 2012. Guide to head diseases of wheat and barley in Montana. Montana State University Extension, Bozeman, Montana.
- Caffrey, K.R., Veal, M.W., 2013. Conducting an agricultural life cycle assessment: challenges and perspectives. *ScientificWorldJournal*. 2013, 472431. doi:10.1155/2013/472431
- Calviño, P.A., Sadras, V.O., Andrade, F.H., 2003. Development, growth and yield of late-sown soybean in the southern Pampas. *Eur. J. Agron.* 19, 265–275. doi:10.1016/S1161-0301(02)00050-3
- Camper, H.M., Genter, C.F., Loope, K.E., 1972. Double cropping following winter barley harvest in Eastern Virginia. *Agron. J.* 64, 1-6. doi:10.2134/agronj1972.00021962006400010001x
- Carter, T.E., Boerma, H.R., 1979. Implications of genotype x planting date and row spacing

- interactions in double-cropped soybean cultivar development. *Crop Sci.* 19, 607–610.
- Castelao Tetila, E., B. Brandoli Machado, N.A. de S. Belete, D.A. Guimaraes, and H. Pistori. 2017. Identification of Soybean Foliar Diseases Using Unmanned Aerial Vehicle Images. *IEEE Geosci. Remote Sens. Lett.* 14(12): 2190–2194. doi: 10.1109/LGRS.2017.2743715.
- Caviglia, O.P., Sadras, V.O., Andrade, F.H., 2011. Yield and quality of wheat and soybean in sole- and double-cropping. *Agron. J.* 103, 1081–1089. doi:10.2134/agronj2011.0019
- Chamberlain, R.S. 2017. rnoaa: “NOAA” Weather Data from R. R Package. version 0.7.0. <https://cran.r-project.org/package=rnoaa>.
- Chang, W.-S.W.-S., Lee, H.-I.H.-I., Hungria, M., Chang, W.-S.W.-S., Lee, H.-I.H.-I., 2015. Soybean Production in the Americas, Principles of Plant-Microbe Interactions. Springer International Publishing, Cham. doi:10.1007/978-3-319-08575-3_41
- Chen, G., Wiatrak, P., 2010. Soybean development and yield are influenced by planting date and environmental conditions in the Southeastern Coastal Plain, United States. *Agron. J.* 102, 1731–1737. doi:10.2134/agronj2010.0219
- Chen, A., J. Reinheimer, A. Brûlé-Babel, U. Baumann, M. Pallotta, G. Fincher., 2009. Genes and traits associated with chromosome 2H and 5H regions controlling sensitivity of reproductive tissues to frost in barley. *Theor. Appl. Genet.* 118(8): 1465–1476. doi: 10.1007/s00122-009-0995-4.
- Chen, A., L. V. Gusta, A. Brûlé-Babel, R. Leach, U. Baumann, G. Fincher., N. Collins., 2009. Varietal and chromosome 2H locus-specific frost tolerance in reproductive tissues of barley (*Hordeum vulgare* L.) detected using a frost simulation chamber. *Theor. Appl. Genet.* 119(4): 685–694. doi: 10.1007/s00122-009-1079-1.
- Chen, S., Kurle, J.E., Stetina, S.R., Miller, D.R., Klossner, L.D., Nelson, G.A., Hansen, N.C., 2007. Interactions between iron-deficiency chlorosis and soybean cyst nematode in Minnesota soybean fields. *Plant Soil* 299, 131–139. doi:10.1007/s11104-007-9370-x
- Chen, T.H., Gusta, L. V, Fowler, D.B., 1983. Freezing injury and root development in winter cereals. *Plant Physiol.* 73, 773–777. doi:10.1104/PP.73.3.773
- Cober, E.R., Voldeng, H.D., 2012. A retrospective look at short-season soybean cultivar development in Ontario. *Can. J. Plant Sci.* 92, 1239–1243. doi:10.4141/cjps2012-032
- Crabtree, R.J., Prater, J.D., Mbolda, P., 1990. Long-term wheat, soybean, and grain sorghum double-cropping under rainfed conditions. *Agron. J.* 82, 683–686.
- Craft Maltsters Guild. 2018. Who Are We? <https://craftmalting.com/the-guild/craft-maltsters-guild/> (accessed 12 July 2019).
- Culman, S., L. Lindsey, M. Loux, P. Paul, and E. Stockinger. 2017. Management of Ohio winter malting barley fall management of ohio malting barley. <https://stepupsoy.osu.edu/sites/hcs-soy/files/barley%20guide.pdf>. Ohio State Univ. Ext., Columbus, OH.

- Dabney, S.M., 1998. Cover crop impacts on watershed hydrology. *J. Soil Water Conserv.* 53, 207–213.
- Daly, C., M.P. Widrlechner, M.D. Halbleib, J.I. Smith, and W.P. Gibson. 2012. Development of a new USDA Plant Hardiness Zone Map for the United States. *J. Appl. Meteorol. Climatol.* 51: 242–264. doi: 10.1175/2010JAMC2536.1.
- Darby, H., Emick, H., Cummings, E., 2017. 2016 Winter Barley Planting Date and Nitrogen Amendment Trial. University of Vermont Extension, Albans, VT.
- Davis, A.S., Hill, J.D., Chase, C.A., Johanns, A.M., Liebman, M., 2012. Increasing cropping system diversity balances productivity, profitability and environmental health. *PLoS One* 7, 1–8. doi:10.1371/journal.pone.0047149
- DeFries, R.S., J.A. Foley, and G.P. Asner. 2004. Land-use choices: balancing human needs and ecosystem function. *Front. Ecol. Environ.* 2(5): 249–257. doi: 10.1890/1540-9295(2004)002[0249:LCBHNA]2.0.CO;2.
- del Moral, M.B.G., del Moral, L.F.G., 1995. Tiller production and survival in relation to grain yield in winter and spring barley. *F. Crop. Res.* 44, 85–93. doi:10.1016/0378-4290(95)00072-0
- Delogu, G., L. Cattivelli, N. Pecchioni, D. De Falcis, T. Maggiore, and A.M Stanca. 1998. Uptake and agronomic efficiency of nitrogen in winter barley and winter wheat. *Eur. J. Agron.* 9:11–20. doi:10.1016/S1161-0301(98)00019-7.
- Dhima, K. V., Vasilakoglou, I.B., Eleftherohorinos, I.G., Lithourgidis, A.S., 2006. Allelopathic potential of winter cereals and their cover crop mulch effect on grass weed suppression and corn development. *Crop Sci.* 46, 345. doi:10.2135/cropsci2005-0186
- Di, H.J., Cameron, K.C., 2002. Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutr. Cycl. Agroecosystems* 46, 237–256.
- DiCicco-Bloom, B., Crabtree, B.F., 2006. The qualitative research interview. *Med. Educ.* 40, 314–321. doi:10.1111/j.1365-2929.2006.02418.x
- Dickson, A.D., Harlan, J.R., Klingman, D.L., Moseman, J.G., Olien, C.R., 1979. Barley: origin, botany, culture, winter hardiness, genetics, utilization, pests - Rev. (ed.). Hyattsville, Md. (USA) US Dept. of Agriculture, Science and Education Administration, Washington, D.C.
- Dillon, K.A., 2014. Double-crop soybean vegetative growth, seed yield, and yield component response to agronomic inputs in the mid-atlantic, USA.
- Dinnes, D.L., Karlen, D.L., Jaynes, D.B., Kaspar, T.C., Hatfield, J.L., Dinnes, D.L., Karlen, D.L., Kaspar, T.C., Hatfield, J.L., Colvin, T.S., Cambardella, C.A., 2002. Review and Interpretation: nitrogen management strategies to reduce nitrate leaching in tile- drained Midwestern soils. *Agron. J* 94, 153–171.
- Dofing, S.M., Schmidt, J.W., 1985. Relationship between subcrown internode length and winter survival in winter barley. *Crop Sci.* 25, 690–692.

- Dong, Y.S., L.M. Zhao, B. Liu, Z.W. Wang, Z.Q. Jin, H. Sun., 2004. The genetic diversity of cultivated soybean grown in China. *Theor. Appl. Genet.* 108(5): 931–936. doi: 10.1007/s00122-003-1503-x.
- Dornbos, D.L., Mullen, R.E., 1992. Soybean seed protein and oil contents and fatty acid composition adjustments by drought and temperature. *J. Am. Oil Chem. Soc.* 69, 228–231. doi:10.1007/BF02635891
- Dunphy, E.J., Hanway, J.J., Green, D.E., 1979. Soybean yields in relation to days between specific developmental stages. *Agron. J.* 71, 917–920.
- Eberle, C.A., Thom, M.D., Nemec, K.T., Forcella, F., Lundgren, J.G., Gesch, R.W., Riedell, W.E., Papiernik, S.K., Wagner, A., Peterson, D.H., Eklund, J.J., 2015. Using pennycress, camelina, and canola cash cover crops to provision pollinators. *Ind. Crops Prod.* 75, 20–25. doi:10.1016/J.INDCROP.2015.06.026
- Egli, D.B., 2011. Time and the productivity of agronomic crops and cropping systems. *Agron. J.* 103, 743–750. doi:10.2134/agronj2010.0508
- Egli, D.B., and P.L. Cornelius. 2009. A regional analysis of the response of soybean yield to planting date. *Agron. J.* 101(2): 330. doi: 10.2134/agronj2008.0148.
- Egli, D.B. 2008. Soybean yield trends from 1972 to 2003 in Mid-Western USA. *F. Crop. Res.* 106(1): 53–59. doi: 10.1016/J.FCR.2007.10.014.
- Egli, D.B., Bruening, W., 1992. Planting date and soybean yield: evaluation of environmental effects with a crop simulation model: SOYGRO*. *Agric. For. Meteorol.* 62, 19–29.
- Egli, D.B., Bruening, W.P., 2000. Potential of early-maturing soybean cultivars in late plantings. *Agron. J.* 92, 532–537. doi:10.2134/agronj2000.923532x
- Eldakak, M., S.I.M. Milad, A.I. Nawar, and J.S. Rohila. 2013. Proteomics: a biotechnology tool for crop improvement. *Front. Plant Sci.* 4: 35. doi: 10.3389/fpls.2013.00035.
- Ellen, J. 1993. Growth, yield and composition of four winter cereals. I. Biomass, grain yield and yield formation. *NJAS wageningen J. life Sci.* 41:153–165. <https://library.wur.nl/ojs/index.php/njas/article/view/628>.
- Elzinga, K.G., Tremblay, C.H., Tremblay, V.J., 2018. Craft Beer in the USA: Strategic connections to macro- and European brewers, in: *Economic Perspectives on Craft Beer*. Springer International Publishing, Cham, pp. 55–88. doi:10.1007/978-3-319-58235-1_2
- Fehr, W.R., and C.E. Caviness. Stages of soybean development. Cooperative Extension Service, Special Report 80. Iowa State University, Ames, Iowa.
- Fishbein, M., I. Ajzen, and I. Ajzen. 2011. *Predicting and Changing Behavior*. Psychology Press, New York.
- Foroud, N., Mundel, H.-H., Saindon, G., Entz, T., 1993. Effect of level and timing of moisture stress on soybean plant development and yield components. *Irrig. Sci.* 13, 149–155. doi:10.1007/BF00190029

- Fowler, D.B., and L.R. Moats. 1995. Winter wheat "Conserve and Win" demonstration and development program. 1995 Soils and Crops Workshop, University of Saskatchewan, Saskatoon, SK. 23–24 Feb. 1995. Univ. of Saskatchewan Ext. Press, Saskatoon, SK.
- Fowler, D.B., B.M. Byrns, and K.J. Greer. 2014. Overwinter low-temperature responses of cereals: Analyses and simulation. *Crop Sci.* 54:2395–2405. doi:10.2135/cropsci2014.03.0196.
- Fowler, D.B., Moats, L.R., 1995. Winter wheat "conserve and win" demonstration and development program. *Soils Crop. Work. Proc.* Winnipeg, Manitoba, CA.
- Fowler, D.B., and L. V. Gusta. 1979. Selection for winterhardiness in wheat. i. identification of genotypic variability I. *Crop Sci.* 19(6): 769–772. doi: 10.2135/cropsci1979.0011183X001900060005x.
- Fraser, P.M., Curtin, D., Harrison-Kirk, T., Meenken, E.D., Beare, M.H., Tabley, F., Gillespie, R.N., Francis, G.S., 2013. Winter nitrate leaching under different tillage and winter cover crop management practices. *Soil Sci. Soc. Am. J.* 77, 1391. doi:10.2136/sssaj2012.0256
- Gaba, S., Lescourret, F., Boudsocq, S., Enjalbert, J., Hinsinger, P., Journet, E.P., Navas, M.L., Wery, J., Louarn, G., Malézieux, E., Pelzer, E., Prudent, M., Ozier-Lafontaine, H., 2015. Multiple cropping systems as drivers for providing multiple ecosystem services: from concepts to design. *Agron. Sustain. Dev.* 35, 607–623. doi:10.1007/s13593-014-0272-z
- Gallagher, J. N. 1983: Winter barley-possibilities, problems and prospects. In: *Barley: Production and Marketing*. Wright, G. M.; Wynn-Williams, R. B. ed. Agronomy Society of New Zealand Special Publication No.2.
- Garstang, J.R., Spink, J.H., Suleimenov, M., Schillinger, W.F., Mckenzie, R.H., Tanaka, D.L., Ceccarelli, S., Grando, S., Paynter, B.H., Fettell, N.A., 2011. Chapter 9: Cultural Practices: Focus on Major Barley-Producing Regions, In *Barley: Production, Improvement, and Uses*. doi:10.1002/9780470958636.ch9, Blackwell Publishing Ltd. Hoboken, NJ.
- Gaudin, A.C.M., Janovicek, K., Martin, R.C., Deen, W., 2014. Approaches to optimizing nitrogen fertilization in a winter wheat–red clover (*Trifolium pratense* L.) relay cropping system. *F. Crop. Res.* 155, 192–201. doi:10.1016/J.FCR.2013.09.005
- Gaudin, A.C.M.M., T.N. Tolhurst, A.P. Ker, K. Janovicek, C. Tortora, Deen, W., 2015. Increasing crop diversity mitigates weather variations and improves yield stability. *PLoS One* 10(2): 1–20. doi: 10.1371/journal.pone.0113261.
- Gava, O., Bartolini, F., Venturi, F., Brunori, G., Zinnai, A., Pardossi, A., Gava, O., Bartolini, F., Venturi, F., Brunori, G., Zinnai, A., Pardossi, A., 2018. A reflection of the use of the life cycle assessment tool for agri-food sustainability. *Sustainability* 11, 71. doi:10.3390/su11010071
- Gay, S., Egli, D.B., Reicosky, D.A., 1980. Physiological aspects of yield improvement in soybeans. *Agron. J.* 72, 387-392. doi:10.2134/agronj1980.00021962007200020031x
- Gesch, R.W., Archer, D.W., 2013. Double-cropping with winter camelina in the northern Corn

- Belt to produce fuel and food. *Ind. Crops Prod.* 44, 718–725. doi:10.1016/J.INDCROP.2012.05.023
- Gesch, R.W., Archer, D.W., Berti, M.T., 2014. Dual cropping winter camelina with soybean in the northern corn belt. *Agron. J.* 106, 1735–1745. doi:10.2134/agronj14.0215
- Goglio, P., G. Brankatschk, M.T. Knudsen, A.G. Williams, and T. Nemecek. 2018. Addressing crop interactions within cropping systems in LCA. *Int. J. Life Cycle Assess.* 23(9): 1735–1743. doi: 10.1007/s11367-017-1393-9.
- Goglio, P., Smith, W.N., Worth, D.E., Grant, B.B., Desjardins, R.L., Chen, W., Tenuta, M., McConkey, B.G., Williams, A., Burgess, P., 2018. Development of Crop.LCA, an adaptable screening life cycle assessment tool for agricultural systems: A Canadian scenario assessment. *J. Clean. Prod.* 172, 3770–3780. doi:10.1016/J.JCLEPRO.2017.06.175
- Goldsmith, P., 2008. Soybean production and processing in brazil, in: contrasting soybean production and processing between the us and brazil. In *Soybeans: Chemistry, production, processing and utilization*, ed. L. Johnson, P. White, and R. Galloway, 773–798. Champaign: AOCS Press.
- Gołębiowska-Pikania, G., P. Kopeć, E. Surówka, M. Krzewska, E. Dubas, Ż. Iwona., 2017. Changes in protein abundance and activity involved in freezing tolerance acquisition in winter barley (*Hordeum vulgare* L.). *J. Proteomics* 169: 58–72. doi: 10.1016/j.jprot.2017.08.019.
- González-García, S., P.C. Morales, and B. Gullón. 2018. Estimating the environmental impacts of a brewery waste-based biorefinery: Bio-ethanol and xylooligosaccharides joint production case study. *Ind. Crops Prod.* 123: 331–340. doi: 10.1016/J.INDCROP.2018.07.003
- Goolsby, D.A., Battaglin, W.A., Aulenbach, B.T., Hooper, R.P., 2001. Nitrogen Input to the Gulf of Mexico. *J. Environ. Qual.* 30, 329–336. doi:10.2134/jeq2001.302329x
- Graefe, D., Mowen, A., Graefe, A., 2018. Craft Beer Enthusiasts' Support for Neolocalism and Environmental Causes, in: *Craft Beverages and Tourism, Volume 2*. Springer International Publishing, Cham, pp. 27–47. doi:10.1007/978-3-319-57189-8_3
- Graner, A., A. Kilian, and A. Kleinhofs. 2010. Barley Genome Organization, Mapping, and Synteny. In: Ullrich, S.E., editor, *Barley*. Wiley-Blackwell, Oxford, UK. p. 63–84
- Grau, C.R., E.S. Oplinger, E.A. Adey, E.A. Hinkens, and M.J. Martinka. 1994. Planting date and row width effect on severity of brown stem rot and soybean productivity. *J. Prod. Agric.* 7:347–351. doi:10.2134/jpa1994.0347
- Gray, G.R., L.P. Chauvin, F. Sarhan, and N. Huner. 1997. Cold acclimation and freezing tolerance (A complex interaction of light and temperature). *Plant Physiol.* 114: 467–474. doi: 10.1104/PP.114.2.467.
- Greilhuber, J., Obermayer, R., 1997. Genome size and maturity group in *Glycine max* (soybean). *Heredity* (Edinb). 78, 547–551. doi:10.1038/hdy.1997.85

- Guo, B., H. Luan, S. Lin, C. Lv, X. Zhang, R. Xu., 2016. Comparative proteomic analysis of two barley cultivars (*Hordeum vulgare* L.) with contrasting grain protein content. *Front. Plant Sci.* 7: 542. doi: 10.3389/fpls.2016.00542.
- Gusta, Hansel, D.S., Schwalbert, R.A., Shoup, D.E., Holshouser, D.L., Parvej, R., Prasad, P.V.V., Ciampitti, I.A., 2019. A Review of Soybean Yield when Double-Cropped after Wheat. *Agron. J.* 111, 677–685. doi:10.2134/agronj2018.06.0371
- Gusta, L.V., and D.B. Fowler. 1979. Cold resistance and injury in winter cereals. In: *Stress physiology in crop plants*. John Wiley and Sons, New York. p. 160–178.
- Hall, J. 2012. Management practices for improved winter survival of winter wheat in North Dakota. North Dakota State University, Fargo, ND. <https://library.ndsu.edu/ir/handle/10365/26671>.
- Hammel, P. 2018. Omaha's barley boys launch malthouse to supply local breweries. *Omaha World-Hearld* . https://www.omaha.com/news/nebraska/omaha-s-barley-boys-launch-malthouse-to-supply-local-breweries/article_e9f13668-4671-52f7-991f-4c441421122c.html (accessed 23 July 2019).
- Hammond, R.B., R.A. Higgins, T.P. Mack, L.P. Pedigo, and E.J. Bechin- ski. 1991. Soybean pest management. In: D. Pimentel, editor, *CRC handbook of pest management in agriculture*. Vol. 3, 2nd ed. CRC, Boca Raton, FL. p. 341–472.
- Hansel, D.S., Schwalbert, R.A., Shoup, D.E., Holshouser, D.L., Parvej, R., Prasad, P.V.V., Ciampitti, I.A., 2019. A Review of Soybean Yield when Double-Cropped after Wheat. *Agron. J.* 111, 677–685. doi:10.2134/agronj2018.06.0371
- Hartman, G.L., West, E.D., Herman, T.K., 2011. Crops that feed the World 2. Soybean—worldwide production, use, and constraints caused by pathogens and pests. *Food Sec.* 5–17. doi:10.1007/s12571-010-0108-x
- Hartwig, N.L., and H.U. Ammon. 2002. Cover crops and living mulches. *Weed Sci.* 50: 688–699. doi: 10.2307/4046641.
- Hatfield, J.L., and C.L. Walthall. 2015. Meeting Global Food Needs: Realizing the Potential via Genetics × Environment × Management Interactions. *Agron. J.* 107(4): 1215-1221. doi: 10.2134/agronj15.0076.
- Hatfield, J.L., L.D. McMullen, and C.S. Jones. 2009. Nitrate-nitrogen patterns in the Raccoon River Basin related to agricultural practices. *J. Soil Water Conserv.* 64(3): 190–199. doi: 10.2489/jswc.64.3.190.
- Haun, J.R. 1973. Visual quantification of wheat development. *Agron. J.* 65:116-119. doi:10.2134/agronj1973.00021962006500010035x.
- Hayes, P., Cuesta-Marcos, A., Fisk, S., Smith, K., 2012. Winter barley goes facultative and heads east—the long march. Oregon State University, Corvallis, OR, and University of Minnesota, St. Paul, MN.
- Heard, J., and D. Domitruk. 2001. Winter survival and spring assessment of winter wheat. Univ. of Mannitoba, Winnipeg, MB, Canada.

- Heatherly, L.G. 2005. Soybean development in the Midsouthern USA related to date of planting and maturity classification. *Crop Manag.* doi: 10.1094/CM-2005-0421-01-RS.
- Heberlein, T.A. 2012. Navigating environmental attitudes. *Conserv. Biol.* 26(4): 583–585. doi: 10.1111/j.1523-1739.2012.01892.x.
- Helms, T.C., Hurburgh, C.R., Lussenden, R.L., Whited, D.A., 1990. Economic Analysis of Increased Protein and Decreased Yield Due to Delayed Planting of Soybean. *jpa* 3, 367. doi:10.2134/jpa1990.0367
- Herridge, David F, Peoples, Mark B, Boddey, Robert M, Herridge, D F, Peoples, M B, Boddey, R M, 2008. Global inputs of biological nitrogen fixation in agricultural systems. *Plant Soil* 1–18. doi:10.1007/s11104-008-9668-3
- Hertrich, J.D., 2013. Topics in Brewing: Malting. *MBAA Tech. Q.* 50, 131–141. doi:10.1094/TQ-50-4-1120-01
- Hmielowski, T. 2017. From Field to Pint: malting barley in the eastern U.S. *Crop. Soils* 50(4): 10. doi: 10.2134/cs2017.50.0504.
- Hoalst-Pullen, N., M.W. Patterson, R.A. Mattord, and M.D. Vest. 2014. Sustainability Trends in the Regional Craft Beer Industry. *The Geography of Beer*. Springer Netherlands, Dordrecht. p. 109–116
- Holland, J.B., Brummer, E.C., 1999. Cultivar effects on Oat – Berseem Clover intercrops. *Agron. J.* 91, 321–329.
- Holshouser, D., 2016. Double-Crop Community Meeting –Mid Atlantic Region. Virginia Coop. Ext. Blackburg, VA.
- Holshouser, D.L., 2014. Double Cropping Soybeans in Virginia. Virginia Coop. Ext. Blackburg, VA.
- Hooper, D.U., F.S. Chapin, J.J. Ewel, A. Hector, P. Inchausti, S. Lavorel, J. H. Lawton, D. M. Lodge, M. Loreau, S. Naeem, B. Schmid, H. Setälä, A. J. Symstad, J. Vandermeer, D. A. Wardle., 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecol. Monogr.* 75(1): 3–35. doi: 10.1890/04-0922.
- Hu, M., Wiatrak, P., 2012. Effect of planting date on soybean growth, yield, and grain quality: Review. *Agron. J.* 104, 785–790. doi:10.2134/agronj2011.0382
- Hunt, N.D., J.D. Hill, and M. Liebman. 2019. Cropping system diversity effects on nutrient discharge, soil erosion, and agronomic performance. *Environ. Sci. Technol.* 53(3): 1344–1352. doi: 10.1021/acs.est.8b02193.
- Jarquín, D., R. Howard, A. Xavier, S. Das Choudhury. 2018. Increasing predictive ability by modeling interactions between environments, genotype and canopy coverage image data for soybeans. *Agronomy* 8(4): 51. doi: 10.3390/agronomy8040051.
- Jedel, P.E., and D.F. Salmon. 1994. Date and rate of seeding of winter cereals in central Alberta. *Can. J. Plant Sci.* 74: 447–453. doi: 10.4141/cjps94-083.

- Johnson, G.A., M.B. Kantar, K.J. Betts, and D.L. Wyse. 2015. Field pennycress production and weed control in a double crop system with soybean in minnesota. *Agron. J.* 107(2): 532–540. doi: 10.2134/agronj14.0292.
- Johnson, G.A., Wells, M.S., Anderson, K., Gesch, R.W., Forcella, F., Wyse, D.L., 2017. Yield tradeoffs and nitrogen between pennycress, camelina, and soybean in relay- and double-crop systems. *Agron. J.* 109, 2128–2135. doi:10.2134/agronj2017.02.0065
- Johnson, L.A., White, P.J., Galloway, R., 2008. Soybeans : Chemistry, Production, Processing, And utilization. AOCS Press. Champaign, IL
- Joon, P.S., Han, K.W., Eun, L.J., Up, K.Y., Chul, S.J., Hwan, R.Y., Chun, S.R., 2005. Nitrogen balance and biological nitrogen fixation of soybean in soybean-barley cropping system. *Korean J. Crop Sci.* 50, 1–4. doi:10.7740/kjcs
- Kandel, H., Endres, G., 2019. Soybean production field guide for North Dakota. North Dakota State Univeristy, Fargo, ND.
- Kane, M. V., Steele, C.C., Grabau, L.J., 1997a. Early-maturing soybean cropping system: I. Yield responses to planting date. *Agron. J.* 89, 454–458. doi:10.2134/agronj1997.00021962008900030014x
- Kane, M. V., Steele, C.C., Grabau, L.J., MacKown, C.T., Hildebrand, D.F., 1997b. Early-Maturing Soybean Cropping System: III. Protein and Oil Contents and Oil Composition. *Agron. J.* 89, 464. doi:10.2134/agronj1997.00021962008900030016x
- Kaspar, T.C., D.B. Jaynes, T.B. Parkin, T.B. Moorman, and J.W. Singer. 2012. Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. *Agric. Water Manag.* 110: 25–33. doi: 10.1016/J.AGWAT.2012.03.010.
- Kaspar, T.C., Radke, J.K., Laflen, J.M., 2001. Small grain cover crops and wheel traffic effects on infiltration, runoff, and erosion, *Journal of Soil and Water Conservation.* 160-164.
- Kaufenberg, B. 2017. Trailblazers 2017: Local malt. The Growler. <https://growlermag.com/trailblazers-2017-local-malt/>.
- Keller, K., N. Kirchgessner, R. Khanna, R. Siegwart, A. Walter, A. Helge. 2018. Soybean leaf coverage estimation with machine learning and thresholding algorithms for field phenotyping. *Proc. BMVC 2018*: 0032. <https://www.research-collection.ethz.ch/handle/20.500.11850/305781> (accessed 20 August 2019).
- Kendall, P.C., 1994. Treating anxiety disorders in children: results of a randomized clinical trial. *J. Consult. Clin. Psychol.* 62, 100–110.
- Keyser, H.H., Li, F., 1992. Potential for increasing biological nitrogen fixation in soybean. *Plant Soil* 141, 119–135. doi:10.1007/BF00011313
- Kirby, E.J.M., Appleyard, M., Fellowes, G., 1985. Variation in development of wheat and barley in response to sowing date and variety. *J. Agric. Sci.* 104, 383–396. doi:10.1017/S0021859600044075

- Kladivko, E.J., Frankenberger, J.R., Jaynes, D.B., Meek, D.W., Jenkinson, B.J., Fausey, N.R., 2004. Nitrate leaching to subsurface drains as affected by drain spacing and changes in crop production system. *J. Environ. Qual.* 33, 1803-1813. doi:10.2134/jeq2004.1803
- Kleban, J., and I. Nickerson. 2011. The US Craft Brew Industry. Allied Academies International Conference International Academy for Case Studies. DreamCatchers Group, LLC, Arden, NC.
- Knapp, W.R., and J.S. Knapp. 1980. Interaction of planting date and fall fertilization on winter barley performance. *Agron. J.* 72:440-445.
doi:10.2134/agronj1980.00021962007200030008x.
- Knodel, J.J., Beauzay, P., Boetel, M., Prochaska, T., Lubenow, L., 2018. 2019 Field crop insect management guide. North Dakota State University. Fargo, ND.
- Kolar, S.C., Hayes, P.M., Chen, T.H.H., Linderman, R.G., 1991. Genotypic variation for cold tolerance in winter and facultative barley. *Crop Sci.* 31, 1149–1152.
doi:10.2135/cropsci1991.0011183X0031000500013x
- Komatsuda, T., Pourkheirandish, M., He, C., Azhaguvel, P., Kanamori, H., Perovic, D., Stein, N., Graner, A., Wicker, T., Tagiri, A., Lundqvist, U., Fujimura, T., Matsuoka, M., Matsumoto, T., Yano, M., 2007. Six-rowed barley originated from a mutation in a homeodomain-leucine zipper I-class homeobox gene. *Proc. Natl. Acad. Sci. U. S. A.* 104, 1424–1429. doi:10.1073/pnas.0608580104
- Kosová, K., P. Vítámvás, and I.T. Prášil. 2014. Wheat and barley dehydrins under cold, drought, and salinity - what can LEA-II proteins tell us about plant stress response? *Front. Plant Sci.* 5: 343. doi: 10.3389/fpls.2014.00343.
- Kusmec, A., de Leon, N., Schnable, P.S., 2018. Harnessing phenotypic plasticity to improve maize yields. *Front. Plant Sci.* 9, 1377-1381. doi:10.3389/fpls.2018.01377
- Kuznetsova, A., P.B. Brockhoff, and R.H.B. Christensen. 2017. lmerTest Package: Tests in linear mixed effects models. *J. Stat. Softw.* 82: 1–26. doi: 10.18637/jss.v082.i13.
- Kyei-Boahen, S., Zhang, L., 2006. Early-Maturing Soybean in a Wheat–Soybean Double-Crop System. *Agron. J.* 98, 295. doi:10.2134/agronj2005.0198
- Lazor, J., 2013. The organic grain grower : small-scale, holistic grain production for the home and market producer. Chelsea Green Pub, White River Junction, Hartford, VT.
- Leat P, Revoredo-Giha C, 2008. Enhancing the integration of agri-food supply chains: theoretical issues and practical challenges in the UK malting barley supply chain. 12th Congress of the European Association of Agricultural Economists – EAAE. Ghent, Belgium.
- Leavy, P. (Ed.). (2014). The Oxford handbook of qualitative research. Oxford: Oxford University Press.
- Levers, L., A. Pradhananga, and J.M. Peterson. 2018. Reducing the environmental impact of corn monoculture: farmer willingness to accept for alternative cropping systems. Agricultural and Applied Economics Association.

- Levitt J. 1980. Responses of plants to environmental stress. New York: Academic Press. 1:166–222.
- Liebman, M., and L.A. Schulte. 2015. Enhancing agroecosystem performance and resilience through increased diversification of landscapes and cropping systems. *Elem. Sci. Anthr.* 3(0): 000041. doi: 10.12952/journal.elementa.000041.
- Litrice, I., Violle, C., 2015. Diversity in plant breeding: a new conceptual framework. *Trends Plant Sci.* 20, 604–613. doi:10.1016/J.TPLANTS.2015.07.007
- Liu, X., Wu, J.-A., Ren, H., Qi, Y., Li, C., Cao, J., Zhang, X., Zhang, Z., Cai, Z., Gai, J., 2017. Genetic variation of world soybean maturity date and geographic distribution of maturity groups. *Breed. Sci.* 67, 221–232. doi:10.1270/jsbbs.16167
- Liu, C., B. Fan, Z. Cao, Q. Su, Y. Wang, Z. Zhang and J. Tian, 2016. Development of a high-density genetic linkage map and identification of flowering time QTLs in adzuki bean (*Vigna angularis*). *Sci. Rep.*, 6: 1-10
- Lorenz, A.J., Naeve, S., Killam, A., Weston, D., 2018. 2018 Soybean Field Crop Trials Results. University of Minnesota, St. Paul, Minnesota.
- Lund, J., 2015. Forever Green: Alternative, off-season crops could benefit economy as well as ecology. Minnesota Environ. Partnersh. URL <https://www.mepartnership.org/alternative-off-season-crops-could-benefit-economy-as-well-as-ecology/> (accessed 2.10.19).
- Luo, Q., 2011. Temperature thresholds and crop production: a review. *Clim. Change* 109, 583–598. doi:10.1007/s10584-011-0028-6
- Mahler, R., O. Guy, S., 2007. Northern Idaho Fertilizer Guide-Winter Barley. University of Idaho Extension, Moscow, ID.
- Makanza, R., M. Zaman-Allah, J. Cairns, C. Magorokosho, A. Tarekegne, M. Olssen, B. Prasanna. 2018. High-throughput phenotyping of canopy cover and senescence in maize field trials using aerial digital canopy imaging. *Remote Sens.* 10(2): 330. doi: 10.3390/rs10020330.
- Mathre, D.E., 1997. Compendium of barley diseases. APS Press. St.Paul, MN.
- Maxwell, S.K., Wood, E.C., Janus, A., 2008. Comparison of the USGS 2001 NLCD to the 2002 USDA Census of Agriculture for the Upper Midwest United States. *Agric. Ecosyst. Environ.* 127, 141–145. doi:10.1016/j.agee.2008.03.012
- McFarland, A., Kapp, C., Researcher, C., Isleib, J., Crops, F., Educator, E., Graham, S., Guild, M.B., 2014. Malting Barley Production in Michigan. Michigan State Univ. Ext. Bull. 1–16. doi:<http://dx.doi.org/10.1186/s12969-015-0053-5>
- McGrath, P.F., and J.S. Bale. 1990. The effects of sowing date and choice of insecticide on cereal aphids and barley yellow dwarf virus epidemiology in northern England. *Ann. Appl. Biol.* 117:31–43. doi:10.1111/j.1744-7348.1990.tb04192.x.
- McGuire, J., L.W. Morton, and A.D. Cast. 2013. Reconstructing the good farmer identity: shifts

- in farmer identities and farm management practices to improve water quality. *Agric. Human Values* 30(1): 57–69. doi: 10.1007/s10460-012-9381-y.
- McLaughlin, R.B., Reid, N., Moore, M.S., 2014. The Ubiquity of good taste: a spatial analysis of the craft brewing industry in the United States, in: *The Geography of Beer*. Springer Netherlands, Dordrecht, pp. 131–154. doi:10.1007/978-94-007-7787-3_13
- McMullen, M., G. Bergstrom, R. Dill-Macky, and G. Shaner. 2012. A united effort to fight an enemy of wheat and barley: *Fusarium Head Blight*. *Plant Dis.* 96, 1712-1728. doi: 10.1094/PDIS-03-12-0291-FE.
- Meynard, J.-M., Jeuffroy, M.-H., Le Bail, M., Lefèvre, A., Magrini, M.-B., Michon, C., 2017. Designing coupled innovations for the sustainability transition of agrifood systems. *Agric. Syst.* 157, 330–339. doi:10.1016/J.AGSY.2016.08.002
- Midwest Cover Crops Council (MCCC), 2012. *Midwest Cover Crops Field Guide*, Second edition. Purdue Univ., West Lafayette, IN.
- Miladinovic, J., Kurosaki, H., Burton, J.W., Hrustic, M., Miladinovic, D., 2006. The adaptability of shortseason soybean genotypes to varying longitudinal regions. *Europ. J. Agronomy.* 25, 243–249.
- Mitchell, D.C., M.J. Castellano, J.E. Sawyer, and J. Pantoja. 2013. Cover crop effects on nitrous oxide emissions: role of mineralizable carbon. *Soil Sci. Soc. Am. J.* 77: 1765-1773. doi: 10.2136/sssaj2013.02.0074.
- Mohammadi, M., Blake, T.K., Budde, A.D., Chao, S., Hayes, P.M., Horsley, R.D., Obert, D.E., Ullrich, S.E., Smith, K.P., 2015. A genome-wide association study of malting quality across eight U.S. barley breeding programs. *Theor. Appl. Genet.* 128, 705–721. doi:10.1007/s00122-015-2465-5
- Moore, K.J., Karlen, D.L., 2013. Double cropping opportunities for biomass crops in the north central USA. *Biofuels* 4, 605–615. doi:10.4155/BFS.13.50
- Morton, L.W., Hobbs, J., Arbuckle, J.G., Loy, A., 2015. Upper Midwest climate variations: farmer responses to excess water risks. *J. Environ. Qual.* 44, 810-822. doi:10.2134/jeq2014.08.0352
- Mourtzinis, S., Conley, S.P., 2017. Delineating soybean maturity groups across the United States. *Agron. J.* 109, 1397–1403. doi:10.2134/agronj2016.10.0581
- Mourtzinis, S., Gaspar, A.P., Naeve, S.L., Conley, S.P., 2017. Planting date, maturity, and temperature effects on soybean seed yield and composition. *Agron. J.* 109, 2040–2049. doi:10.2134/agronj2017.05.0247
- Muckey, E. 2018. *Small Grains in Minnesota: Assessing the Feasibility of Local Supply Chains*. <https://conservancy.umn.edu/handle/11299/200086> (accessed 20 June 2019).
- Muñoz-Amatriaín, M., Cistué, L., Xiong, Y., Bilgic, H., Budde, A.D., Schmitt, M.R., Smith, K.P., Hayes, P.M., Muehlbauer, G.J., 2010. Structural and functional characterization of a winter malting barley. *Theor. Appl. Genet.* 120, 971–984. doi:10.1007/s00122-009-1225-9

- Nafziger, E.D., 2012. Cropping systems. *Illinois Agronomy Handbook*.
<http://extension.cropsi.illinois.edu/handbook/> (accessed: 8 March 2019]
- Nassauer, J.I. Rural landscape change as a product of US federal policy. In: Primdahl, J. and Swaffield, S., editors, *Globalisation and Agricultural Landscapes*. Cambridge University Press, Cambridge. p. 185–200.
- Natalie Daher. 2016. Rahr debuts world's largest single-site malting facility in Shakopee. *Star Trib*. <http://www.startribune.com/rahr-debuts-world-s-largest-single-site-malting-facility-in-shakopee/402005075/> (accessed 13 January 2018).
- National Agricultural Statistics Service (NASS), 2010. Field Crops Usual Planting and Harvesting Dates, *Agricultural Handbook Number 628*, National Agricultural Statistics Service. Washington, DC.
- National Agricultural Statistics Service (NASS), 2018. Crop Production. Washington, D.C.
- National Agricultural Statistics Service, 2018. Crop Production Historical Track Records. Washington, DC.
- National Agricultural Statistics Service, 2018. Crop Production Historical Track Records. Washington, DC.
- Nemecek, T., F. Hayer, E. Bonnin, B. Carrouée, A. Schneider, C. Viver., 2015. Designing eco-efficient crop rotations using life cycle assessment of crop combinations. *Eur. J. Agron.* 65: 40–51. doi: 10.1016/J.EJA.2015.01.005.
- Nleya, T., and J.R. Rickertsen. 2014. Winter wheat response to planting date under dryland Conditions. *Agron. J.* 106:915–924. doi:10.2134/agronj13.0417.
- Noland, R., Wells, M.S., Peterson, H., 2018. Enhancing cover crop nitrogen uptake with improved establishment, better crops with plant food. *Agron*doi:10.24047/BC102231
- Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. *J. Clean. Prod.* 140, 399–409. doi:10.1016/j.jclepro.2016.06.071
- O'Leary, N., Smith, M.E., 1999. Breeding corn for adaptation to two diverse intercropping companions. *Am. J. Altern. Agric.* doi:10.2307/44503118
- Obert, D.E., C.P. Evans, J.M. Windes, D.M. Wesenberg, S.E. Ulrich, A. Budde, X. Chen, E. W. Jackson., 2009. Registration of 'Endeavor' Winter Barley. *J. Plant Regist.* 3(2): 124–126. doi: 10.3198/jpr2008.10.0618crc.
- Opara, L.U. 2003. Traceability in agriculture and food supply chain: A review of basic concepts, technological implications, and future prospects. *Food, Agric. Environ.* 1(1): 101–106. <https://www.semanticscholar.org/paper/Traceability-in-agriculture-and-food-supply-chain%3A-Opara/4f632b6ec4bd1ebdc53a0fcf295b1cd3800ed11e> (accessed 27 July 2019).
- Ott, M.A., Eberle, C.A., Thom, M.D., Archer, D.W., Forcella, F., Gesch, R.W., Wyse, D.L., 2019. Economics and agronomics of relay-cropping pennycress and camelina with soybean

- in Minnesota. *Agron. J.* 111, 1281–1292. doi:10.2134/agronj2018.04.0277
- Panter, D.M., and F.L. Allen. 1989. Simulated selection for superior yielding soybean lines in conventional vs. double-crop nursery environments. *Crop Sci.* 1341–1347.
- Parmar, B.L., Freeman, R.E., Harrison, J.S., Wicks, A.C., Purnell, L., de Colle, S., 2010. Stakeholder Theory: *The State of the Art*. *Acad. Manag. Ann.* 4, 403–445. doi:10.1080/19416520.2010.495581
- Patton, E. M. 2016. The agricultural growth and malting production of barley grains in Northeast Tennessee and Southwest Virginia. East Tennessee State University, Johnson City, Tennessee. <https://dc.etsu.edu/etd> (accessed 7 July 2019).
- Paulitz, T.C., Steffenson, B.J., 2011. Biotic Stress in Barley: Disease Problems and Solutions, in: *Barley*. Wiley-Blackwell, Oxford, UK, pp. 307–354. doi:10.1002/9780470958636.ch11
- Pedersen, P., Lauer, J.G., 2004. Soybean growth and development in various management systems and planting dates. *Crop Sci.* 44, 508–515. doi:10.2135/cropsci2004.0508
- Peterson, H.C., 2013. Fundamental principles of managing multi-stakeholder engagement. *Int. Food Agribus. Manag. Rev.* 16, 11–22. doi:issn #: 1559-2448
- Pfeiffer, T.W., 2000. Selecting soybean for adaptation to double cropping on the basis of full season plant height. *Crop Sci.* 387–390.
- Pfeiffer, T.W., L.J. Grabau, and J.H. Orf. 1995. Early maturity soybean production system: Genotype x environment interaction between regions of adaptation. *Crop Sci.* 35(1): 108–112. doi: 10.2135/cropsci1995.0011183X003500010020x.
- Pimbert, M., R. Shindelar, and H. Schösler. 2015. Think Global, Eat Local Exploring Foodways. Rachel Carson Center for Environment and Society, Munich, Germany.
- Purcell, C. 2018. Miller hopes to strike ‘Black Gold’ with barley. *Cascade Pioneer*. http://www.cdpioneer.com/news/article_9108d9cb-1513-5066-b425-c76be6201ac8.html (accessed 23 July 2019).
- Purcell, L.C., Ball, R. a, Reaper, J.D., Vories, E.D., 2002. Radiation use efficiency and biomass production in soybean at different plant population densities. *Crop Sci.* 42, 172–177. doi:10.2135/cropsci2002.1720
- Purcell, L.C., Sinclair, T.R., McNew, R.W., 2003. Drought avoidance assessment for summer annual crops using long-term weather data. *Agron. J.* 95, 1566–1576. doi:10.2134/agronj2003.1566
- R Core Team, 2018. R: A language and environment Computing, statistical computing. Vienna, Austria.
- Ramankutty, N., Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M., Rieseberg, L.H., 2018. Trends in global agricultural land use: implications for environmental health and food security. *Annu. Rev. Plant Biol.* 69, 789–815. doi:10.1146/annurev-arplant-042817-040256
- Raun, W.R., Johnson, G.V., 1999. Improving nitrogen use efficiency for cereal production.

Agron. journal.

- Richter, E., Hooker, D., Hohner, H., 2013. Crop Advances: Field Crop Reports Double Cropping Soybeans in Ontario. University of Guelph, Guelph, Ontario CA.
- Robertson, G.P., Allen, V.G., Boody, G., Boose, E.R., Creamer, N.G., Drinkwater, L.E., Gosz, J.R., Lynch, L., Havlin, J.L., Jackson, L.E., Pickett, S.T.A., Pitelka, L., Randall, A., Reed, A.S., Seastedt, T.R., Waide, R.B., Wall, D.H., 2008. Long-term agricultural research: a research, education, and extension imperative. *Bioscience* 58, 640–645. doi:10.1641/B580711
- Robertson, G.P., Swinton, S.M., 2005. Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture. *Front. Ecol. Environ.* 3, 38–46. doi:10.1890/1540-9295(2005)003[0038:RAPAEI]2.0.CO;2
- Roesch-McNally, G.E., Basche, A.D., Arbuckle, J.G., Tyndall, J.C., Miguez, F.E., Bowman, T., Clay, R., 2017. The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. *Renew. Agric. Food Syst.* 1–12. doi:10.1017/S1742170517000096
- Roesch-McNally, G.E., J.G. Arbuckle, and J.C. Tyndall. 2018. Barriers to implementing climate resilient agricultural strategies: The case of crop diversification in the U.S. Corn Belt. *Glob. Environ. Chang.* 48: 206–215. doi: 10.1016/J.GLOENVCHA.2017.12.002.
- Roth, G.W., Kirt, A., Collins, A., 2016. Malting Barley in Pennsylvania. Pennsylvania State University, State College, PA.
- Rowntree, S.C., Suhre, J.J., Weidenbenner, N.H., Wilson, E.W., Davis, V.M., Naeve, S.L., Casteel, S.N., Diers, B.W., Esker, P.D., Conley, S.P., 2014. Physiological and phenological responses of historical soybean cultivar releases to earlier planting. *Crop Sci.* 54, 804–816. doi:10.2135/cropsci2013.06.0428
- Runck, B.C., Kantar, M.B., Jordan, N.R., Anderson, J.A., Wyse, D.L., Eckberg, J.O., Barnes, R.J., Lehman, C.L., DeHaan, L.R., Stupar, R.M., Sheaffer, C.C., Porter, P.M., 2014. The Reflective plant breeding paradigm: a robust system of germplasm development to support strategic diversification of agroecosystems. *Crop Sci.* 54, 1939–1949. doi:10.2135/cropsci2014.03.0195
- Russell, K., 2017. Genotype \times Environment \times Management : Implications for selection to heat stress tolerance and nitrogen use efficiency in Soft Red Winter Wheat. University of Kentucky, Louisville, KY.
- Sacks, W.J., D. Deryng, J.A. Foley, and N. Ramankutty. 2010. Crop planting dates: an analysis
- Salmen, L.F. 2000. Beneficiary assessment for agricultural extension : a manual of good practice. : 1–20. <http://documents.worldbank.org/curated/en/660461468337246638/Beneficiary-assessment-for-agricultural-extension-a-manual-of-good-practice> (accessed 22 July 2019).
- Salmeron, M., Gbur, E.E., Bourland, F.M., Buehring, N.W., Earnest, L., Fritschi, F.B., Golden, B.R., Hathcoat, D., Lofton, J., Miller, T.D., Neely, C., Shannon, G., Udeigwe, T.K., Verbree, D.A., Vories, E.D., Wiebold, W.J., Purcell, L.C., 2014. Soybean maturity group choices for early and late plantings in the midsouth. *Agron. J.* 106, 1893–1901.

doi:10.2134/agronj14.0222

- Salmerón, M., Gbur, E.E., Bourland, F.M., Buehring, N.W., Earnest, L., Fritschi, F.B., Golden, B.R., Hathcoat, D., Lofton, J., McClure, A.T., Miller, T.D., Neely, C., Shannon, G., Udeigwe, T.K., Verbree, D.A., Vories, E.D., Wiebold, W.J., Purcell, L.C., 2016. Yield response to planting date among soybean maturity groups for irrigated production in the US Midsouth. *Crop Sci.* 56, 747. doi:10.2135/cropsci2015.07.0466
- Sandler, L.N., 2014. Relay- and double-crop production systems for wheat. University of Missouri, Columbia, MO.
- SARE CTIC, 2017. Annual Report 2016-2017 Cover Crop Survey, Joint publication of the Conservation Technology Information Center, the North Central Region Sustainable Agriculture Research and Education Program, and the American Seed Trade Association. Washington, DC. doi:10.3929/ethz-a-007116300
- Seifert, C. a, Lobell, D.B., 2015. Response of double cropping suitability to climate change in the United States. *Environ. Res. Lett.* 10, 024002. doi:10.1088/1748-9326/10/2/024002
- Setiyono, T.D., Weiss, A., Specht, J., Bastidas, A.M., Cassman, K.G., Dobermann, A., 2007. Understanding and modeling the effect of temperature and daylength on soybean phenology under high-yield conditions. *F. Crop. Res.* 257–271. doi:10.1016/j.fcr.2006.07.011
- Shank, D.B., Adams, M.W., 1960. Environmental variability within inbred lines and single crosses of maize. *J. Genet.* 57, 119–126. doi:10.1007/BF02985341
- Sheaffer, C.C., Moncada, K.M., 2012. Introduction to Agronomy : Food, Crops, and Environment. Delmar Cengage Learning, Clifton Park, NY.
- Shrestha, R.K., Lindsey, L.E., 2019. Agronomic management of malting barley and research needs to meet demand by the craft brew industry. *Agron. J.* 111, 1570–1580. doi:10.2134/agronj2018.12.0787
- Singer, J.W., S.M. Nusser, and C.J. Alf. 2007. Are cover crops being used in the US Corn Belt? *J. Soil Water Conserv.* 62: 353–358. http://www.food.actapol.net/pub/6_3_2007.pdf.
- Singh, R.J., Hymowitz, T., 1999. Soybean genetic resources and crop improvement. *Genome* 42, 605–616. doi:10.1139/g99-039
- Sipperly, E., K. Edinger, N. Ziegler, and E. Roberts. 2014. Comparative Cradle to Gate Life Cycle Assessment of 100% Barley-based Singha Lager Beer in Thailand. Bangkok, Thailand.
- Smith, B.G., 2008. Developing sustainable food supply chains. *Philos. Trans. R. Soc. B Biol. Sci.* 363, 849–861. doi:10.1098/rstb.2007.2187
- Smith, J.R., Nelson, R.L., 1986. Selection for seed-filling period in soybean. *Crop Sci.* 26, 466–469.
- Specht, J.E., Rees, J.M., Zoubek, G.L., Glewen, K.L., Schneider, J.W., Vyhnaelek, A.R., VanDeWalle, B.S., Varner, D.L., 2012. Soybean Planting Date-When and Why. Lincoln, NE.

- Springer, P., 2018. Consumers, craft brewers behind shift that has barley growers, maltsters adjusting. INFORUM Forum Commun. Co. Orlando, FL.
- Stanek, E.C., Lovell, S.T., Reisner, A., 2019. Designing multifunctional woody polycultures according to landowner preferences in Central Illinois. *Agrofor. Syst.* 1–19. doi:10.1007/s10457-019-00350-2
- Staver, K.W., Brinsfield, R.B., 1998. Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic Coastal Plain. *J. Soil Water Conserv.* 53, 230–240.
- Stempel, N.D. 2016. Driving the New York State hop industry to meet demand. Massachusetts Institute of Technology, Cambridge, MA. <https://dspace.mit.edu/handle/1721.1/107507> (accessed 26 April 2019).
- Stoyanova, J., 1996. Growth, nodulation and nitrogen fixation in soybean as affected by air humidity and root temperature. *Biol. Plant.* 38, 537–544. doi:10.1007/BF02890604
- Struthers, D., and K. Greer. 2001. Basics of cold tolerance and winter survival in winter wheat. Manitoba Agronomists Conference. Winnipeg, MB, Canada.
- Stuthman, D.D., Leonard, K.J., Miller-Garvin, J., 2007. Breeding crops for durable resistance to disease. *Adv. Agron.* 95, 319–367. doi:10.1016/S0065-2113(07)95004-X
- Sustainable Food Lab, and Practical Farmers of Iowa. 2015. Expanding the production of oats and small grains in Iowa and Minnesota. Ames, IA.
- Szűcs, P., Skinner, J.S., Karsai, I., Cuesta-Marcos, A., Haggard, K.G., Corey, A.E., Chen, T.H.H., Hayes, P.M., 2007. Validation of the VRN-H2/VRN-H1 epistatic model in barley reveals that intron length variation in VRN-H1 may account for a continuum of vernalization sensitivity. *Mol. Genet. Genomics* 277, 249–261. doi:10.1007/s00438-006-0195-8
- Tamburini, E., P. Pedrini, M. Marchetti, E. Fano, G. Castaldelli., 2015. Life cycle based evaluation of environmental and economic impacts of agricultural productions in the Mediterranean Area. *Sustainability* 7(3): 2915–2935. doi: 10.3390/su7032915.
- Thomas, D., 2013. Malting: the latest craft. *Brew. Distill. Int.* 47–49.
- Thomason, W., Chim, B.K., Holshouser, D., Behl, H., Balota, M., Xia, K., Frame, W., Black, T., 2017. Comparison of full-season and double-crop soybean and grain sorghum systems in Central and Southeastern Virginia. *Agron. J.* 109, 1532–1539. doi:10.2134/agronj2016.10.0577
- Tiemann, L.K., Grandy, A.S., Atkinson, E.E., Marin-Spiotta, E., McDaniel, M.D., 2015. Crop rotational diversity enhances belowground communities and functions in an agroecosystem. *Ecol. Lett.* 18, 761–771. doi:10.1111/ele.12453
- Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. *Nature* 418, 671–677. doi:10.1038/nature01014

- Tutor, A.R., 2012. Effect of Soybean Planting Date in North and South Carolina on Advancing Soybean Varieties in Soybean Breeding. The University of Tennessee at Martin. Martin, Tennessee.
- Ullrich, S.E. 2010. Significance, Adaptation, Production, and Trade of Barley. In S.E. Ullrich (ed.) Barley: Production, improvement, and uses. Wiley-Blackwell, Oxford, UK. p. 3–13.
- USDA-Economic Research Service, 2017. Soybeans and Oil Crops- Background. Washington, DC.
- USDA-Foreign Agricultural Service, 2019. World Agricultural Production. Washington, DC.
- USDA-Natural Resources Conservation Service, 2016. Plant Guide-BARLEY *Hordeum vulgare* L. Washington, DC.
- USDA. 2019. USDA/NASS 2018 State Agriculture Overview for Minnesota. Washington, DC.
- USDA National Agricultural Statistics Services. 2010. Field crops usual planting and harvesting dates (Agricultural Handbook Number 628). USDA, Washington, DC.
- Varvel, G.E., Peterson, T.A., 1990. Residual soil nitrogen as affected by continuous, two-year, and four-year crop rotation systems. *Agron. J.* 82, 958-962.
doi:10.2134/agronj1990.00021962008200050024x
- Verbeten, B., K. Ganoe, J. O’Dea, G. Bergstrom, and M. Sorrells. 2014. Factors influencing malting barley winter survival in 2014. Cornell Univ. Coop. Ext., Ithaca, NY.
- Vico, G., V. Hurry, and M. Weih. 2014. Snowed in for survival: Quantifying the risk of winter damage to overwintering field crops in northern temperate latitudes. *Agric. For. Meteorol.* 197:65–75. doi:10.1016/J.AGRFORMET.2014.06.003.
- von Zitzewitz, J., Szűcs, P., Dubcovsky, J., Yan, L., Francia, E., Pecchioni, N., Casas, A., Chen, T.H.H., Hayes, P.M., Skinner, J.S., 2005. Molecular and structural characterization of barley vernalization genes. *Plant Mol. Biol.* 59, 449–467. doi:10.1007/s11103-005-0351-2
- Wang, Y., Xian, Z., Gai, J., 2001. Classification and geographical distribution of the maturity groups of summer planting soybeans in China. *Chinese J. Ecol.* 20, 1–3.
- Weaver, D.B., R.L. Akridge, and C.A. Thomas. 1991. Growth habit, planting date, and row-spacing effects on late-planted soybean. *Crop Sci.* 31(3): 805. doi: 10.2135/cropsci1991.0011183X003100030052x.
- Werkheiser, I., and S. Noll. 2014. From food justice to a tool of the status quo: three sub-movements within local food. *J. Agric. Environ. Ethics* 27(2): 201–210. doi: 10.1007/s10806-013-9459-6.
- Wesley, R.A., 1999. Double Cropping Wheat And Soybeans In Soybean Production in the Midsouth. CRC Press, Boca Raton, FL.
- Wiersma, J.J. 2006. Winter wheat in Minnesota. Univ. of Minnesota Ext., St. Paul, MN.
- Wilcox, J.R., 2001. Sixty years of improvement in publicly developed elite soybean lines. *Crop*

- Sci. 41, 1711–1716. doi:10.2135/cropsci2001.1711
- Wilcox, J.R., Frankenberger, E.M., 1987. Indeterminate and determinate soybean responses to planting date. *Agron. J.* 79, 1074–1078. doi:10.2134/agronj1987.00021962007900060025x
- Wilkerson, G.G., J.W. Jones, K.J. Boote, and G.S. Buol. 1989. Photoperiodically sensitive interval in time to flower of soybean. *Crop Sci.* 29(3): 721. doi: 10.2135/cropsci1989.0011183X002900030037x.
- William, B. 2019. Beer here: Taproom boom takes root across Minnesota. *MPR News*. <https://www.mprnews.org/story/2019/05/15/taproom-beer-minnesota-growth-surly> (accessed 18 June 2019).
- Wilson, R.F., 2004. Seed Composition, in: Boerma, H.R., Specht, J.E. (Eds.), *Soybeans: Improvement, Production, and Uses*. doi:10.2134/agronmonogr16.3ed.c13
- Windels, C.E. 2000. Economic and social impacts of Fusarium Head Blight: changing farms and rural communities in the Northern Great Plains. Montreal, Quebec, Canada.
- Windes, J.M., and D. Obert. 2009. Charles Two-Row Winter Malt Barley. University of Idaho Extension, Moscow, ID.
- Wise, C., Hashemi, M., Aronson, T., 2016. Date of planting and nitrogen management for malt barley production in the Northeast US. Amherst, MA.
- Wrather, J.A., Ram, ; H H, Yorinori, J.T., 1997. Soybean disease loss estimates for the top 10 soybean producing countries in 1994. *Plant Dis.* 81, 107–110.
- Wright, J., Wilcke, B., Stienstra, W., Schmitt, M., Sands, G., Rehm, G., Potter, B., Ostlie, K., Olson, K., Morey, V., Miller, G., MacRae, I., Lamb, J., Hofman, V., Herzfeld, D., Hellevang, K., Gunsolus, J., Durgan, B., Crookston, K., Breneman, D., 1999. The Minnesota soybean field book. University of Minnesota Extension. St Paul, MN.
- Xavier, A., Jarquin, D., Howard, R., Ramasubramanian, V., Specht, J.E., Graef, G.L., Beavis, W.D., Diers, B.W., Song, Q., Cregan, P.B., Nelson, R., Mian, R., Shannon, J.G., McHale, L., Wang, D., Schapaugh, W., Lorenz, A.J., Xu, S., Muir, W.M., Rainey, K.M., 2018. Genome-wide analysis of grain yield stability and environmental interactions in a multiparental soybean population. *G3.* 8, 519–529. doi:10.1534/g3.117.300300
- Xu, M., Xu, Z., Liu, B., Kong, F., Tsubokura, Y., Watanabe, S., Xia, Z., Harada, K., Kanazawa, A., Yamada, T., Abe, J., 2013. Genetic variation in four maturity genes affects photoperiod insensitivity and PHYA-regulated post-flowering responses of soybean. *BMC Plant Biol.* 13, 91. doi:10.1186/1471-2229-13-91
- Yamoah, C.F., Varvel, G.E., Waltman, W.J., Francis, C.A., 1998. Long-term nitrogen use and nitrogen-removal index in continuous crops and rotations. *F. Crop. Res.* 57, 15–27. doi:10.1016/S0378-4290(97)00109-3
- Ye, S., 2017. Economic impact of the Minnesota biodiesel industry, Minnesota Department of Agriculture. St. Paul, MN.

- Yu, N., L. Li, N. Schmitz, L.F. Tian, J.A. Greenberg, B. Diers. 2016. Development of methods to improve soybean yield estimation and predict plant maturity with an unmanned aerial vehicle based platform. doi: 10.1016/j.rse.2016.10.005.
- Zeiss, M.R., and T.H. Klubertanz. 1994. Sampling programs for soybean arthropods. In: L.P. Pedigo and G.D. Buntin, editors, Handbook of sampling methods for arthropods in agriculture. CRC, Boca, Raton, FL. p. 539–601.
- Zhang, J., Song, Q., Cregan, P.B., Nelson, R.L., Wang, X., Wu, J., Jiang, G.-L., 2015. Genome-wide association study for flowering time, maturity dates and plant height in early maturing soybean (*Glycine max*) germplasm. BMC Genomics 16, 217. doi:10.1186/s12864-015-1441-4
- Zhang, L.X., Kyei-Boahen, S., Zhang, J., Zhang, M.H., Freeland, T.B., Watson, C.E., Liu, X., 2007. Modifications of optimum adaptation zones for soybean maturity groups in the USA. Crop Manag. 6, 1–10. doi:10.1094/CM-2007-0927-01-RS.Abstract
- Zhong, B., Wiersma, J., Steffenson, B., Smith, K., 2019 (Accepted). Assessment of winter barley in minnesota: relationships among cultivar, fall seeding date, winter survival, and grain yield. Crop, Forage and Turfgrass Management.
- Zhou, M.X., 2009. Barley Production and Consumption. Springer, Berlin, Heidelberg, pp. 1–17. doi:10.1007/978-3-642-01279-2_1
- Zhu, Y., Fox, R.H., 2003. Corn-soybean rotation effects on nitrate leaching. Agron. J. 95, 1028–1033. doi:10.2134/agronj2003.1028